



Laukkanen, T., Lipponen, J., Kunutsor, S., Zaccardi, F., Araújo, C. G. S., Mäkikallio, T. H., Khan, H., Willeit, P., Lee, E., Poikonen, S., Tarvainen, M., & Laukkanen, J. (2019). Recovery from sauna bathing favorably modulates cardiac autonomic nervous system. *Complementary Therapies in Medicine*, 45, 190-197.
<https://doi.org/10.1016/j.ctim.2019.06.011>

Peer reviewed version

License (if available):
CC BY-NC-ND

Link to published version (if available):
[10.1016/j.ctim.2019.06.011](https://doi.org/10.1016/j.ctim.2019.06.011)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the author accepted manuscript (AAM). The final published version (version of record) is available online via Elsevier at <https://www.sciencedirect.com/science/article/pii/S0965229919301943>. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

Manuscript Details

Manuscript number	CTIM_2019_186_R2
Title	Recovery from sauna bathing favorably modulates cardiac autonomic nervous system
Article type	Full Length Article

Abstract

Objective: Sauna bathing is becoming a common activity in many countries and it has been linked to favorable health outcomes. However, there is limited data on the heart rate (HR) and heart rate variability (HRV) responses to an acute sauna exposure. Design: We conducted a single-group, time series longitudinal study utilizing a pre-post design to examine acute effects of sauna bathing on the autonomic nervous system as reflected by HRV. A total of 93 participants (mean [SD] age: 52.0 [8.8] years, 53.8% males) with cardiovascular risk factors were exposed to a single sauna session (duration: 30 minutes; temperature: 73°C; humidity: 10-20%) and data on HRV variables were collected before, during and after sauna. Results: Time and frequency-domain HRV variables were significantly modified ($p < 0.001$) by the single sauna session, with most of HRV variables tending to return near to baseline values after 30 minutes recovery. Resting heart rate was lower at the end of recovery (68/min) compared to pre-sauna (77/min). A sauna session transiently diminished the vagal component, whereas the cooling down period after sauna decreased low frequency power ($p < 0.001$) and increased high frequency power in HRV ($p < 0.001$), favorably modulating the autonomic nervous system balance. Conclusions: This study demonstrates that a session of sauna bathing induces an increase in heart rate. During the cooling down period from sauna bathing, HRV increased which indicates the dominant role of parasympathetic activity and decreased sympathetic activity of cardiac autonomic nervous system. Future randomized controlled studies are needed to show if HR and HRV changes underpins the long-term cardiovascular effects induced by regular sauna bathing.

Keywords	sauna bathing, heat therapy, heart rate variability, cardiovascular response
Taxonomy	Human Activity in Medical Context, Clinical Finding
Manuscript category	Public Health Research
Corresponding Author	Jari Antero Laukkanen
Order of Authors	Tanjaniina Laukkanen, Jukka Lipponen, Setor Kunutsor, Francesco Zaccardi, Claudio Gil Araujo, Timo Mäkikallio, Hassan Khan, Peter Willeit, Earric Lee, Sanna Poikonen, Mika Tarvainen, Jari Antero Laukkanen
Suggested reviewers	Daniel Gagnon, Joy Hussain

Submission Files Included in this PDF

File Name [File Type]

covering letter R2.doc [Cover Letter]

CTIM_responses_2019_15_06_R2.docx [Response to Reviewers]

Manuscript Sauna and HRV_R2_Final 15_06_2019.docx [Review Reports]

Highlights.docx [Highlights]

Title page.docx [Title Page (with Author Details)]

Manuscript Sauna and HRV_R2_Final 15_06_2019_clean.docx [Manuscript File]

Supplementary Figure 1_R1.docx [e-Component]

Supplementary Figure 2_R1.pptx [e-Component]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

UNIVERSITY OF EASTERN FINLAND
Institute of Public Health and Clinical Nutrition
15 June 2019

Jari Laukkanen, MD, PhD
Institute of Public Health and Clinical Nutrition
University of Eastern Finland
P.O. Box 1627
70211 Kuopio
Tel: +358-17-162910
Fax: +358-17-162936
E-mail: jariantero.laukkanen@uef.fi

Dear Editor-in-Chief,

We herewith submit the revised (R2) manuscript entitled "Recovery from sauna bathing favorably modulates cardiac autonomic nervous system" for publication in the *Complementary Therapies in Medicine*.

The manuscript has considerably improved after new extensive revision. Additional review round was helpful to clarify more methodological issues with regard to the assessment of heart rate and heart rate variability. We have responded all comments as well as possible taking into account our novel study setting during the sauna bathing conditions. We have planned our experiments as carefully as possible using typical Finnish sauna exposure and recovery period with many necessary measurements included in the study (Laukkanen T, Kunutsor SK, Zaccardi F, et al. Acute effects of sauna bathing on cardiovascular function. *J Hum Hypertens*. 2018;32:129-138).

All authors should have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted. The manuscript has not been published and is not being considered for publication elsewhere, in whole or in part, in any language. The material is original research, has not been previously published and has not been submitted for publication elsewhere while under consideration. There are no any financial or other relationships that might lead to a conflict of interest; no conflict of interest exists.

We prepared the revised manuscript in a balanced fashion and cordially submit it your high-quality journal. We would be grateful if you would consider this revised version for publication in the *Complementary Therapies in Medicine*.

Yours sincerely,

Jari A. Laukkanen, MD, PhD,
Cardiologist, Professor

Revision II

Reviewer 1

Now, only a few very minor comments:

1) There are a few sentences in the discussion that are still a bit confusing:

-p.12, first sentence of discussion: advise getting rid of the word 'variables', keep 'parameters'.

RE: Thank you for your suggestion, we have changed it.

-p.12-13 top sentence, "It has been previously reported that a single sauna session induced a significant alteration of autonomic cardiovascular control in patients with untreated hypertension, with an increased sympathetic and decreased parasympathetic activity." The end of it is not clear - I think instead of 'with an', maybe say 'who generally experience' to specify that it is the people with untreated HTN who have the increased sympathetic and decreased parasympathetic activity? Am I understanding this correctly? The next sentence is then also unclear. Maybe specify the positive alterations referred to?

RE: Thank you for your suggestion, we have revised this text.

-p.13 - last sentence, "Our study showed that the mean HR increased from 77 beats per minute to 120 beats per minute, while the...."

I advise adding 'the mean' for better clarification.

RE: Thank you, the wording has been changed

-p.16 - last paragraph, first sentence, "This study showed the acute effects of a typical Finnish sauna on HR and HRV in a regularly bathing population with cardiovascular risk factors." Again, it is important to clarify that this population already regularly sauna bathes.

RE: Yes, this has been added.

2. In the References section, there is a double reference? Ref #10 and #38 are the same reference.

RE: We have deleted another one:

38. Stanley J, Halliday A, D'Auria S, Buchheit M, Leicht AS. Effect of sauna-based heat acclimation on plasma volume and heart rate variability. Eur J Appl Physiol. 2015;115:785-794.

Otherwise, this manuscript is looking much improved.

RE: Thank you for the enthusiastic comment.

Reviewer 3

I thank the authors for considering my comments. However, several points were not considered nor addressed in the manuscript:

1) I remain unconvinced that the conditions were sufficiently standardized to ensure resting values of pre-sauna HR and HRV:

A - The duration and conditions of the pre-sauna period are not reported. Notably, how long did this period last? Were participants seated in the same chair as the post-sauna measurements? Were they allowed to move/talk?

RE: Thank you for your constructive suggestion. Participants were seated at least 10 minutes in the chair in the quiet lounge room before and after sauna when HR and HRV data was collected. This was added in the method section (on page 8).

B - Data analysis for HR and HRV is not indicated for the pre-sauna period: Were data averaged over a fixed duration for every participant? Were data taken from the last X minutes of the pre-sauna period for every participant?

RE: Thank you for this comment. The most stable 5min part of the pre-sauna period was selected to be first (pre-sauna) analysis sample. Starting times of the first sample may have varied between 6-20 min before the sauna entrance, due to other measurements.

C - To address my comment, the authors could provide in figure format minute averages of HR throughout the intervention, to ensure HR had stabilized during the pre-sauna period.

RE: Thank you for your excellent and pertinent comment. Resting HR and HRV values may always vary due to the psychological tension induced by the measurement conditions and the subject's body posture. We would like to clarify, in more detailed way below, how HR and HRV data were assessed.

HR and HRV measurements were collected from six different assessment moments at stable sitting position before, during and after the sauna exposure (time 1 = before sauna; 2 = 5-10 minutes in sauna; 3 = 15-20 minutes in sauna; 4 = 25-30 minutes in sauna; 5 = 2-7 minutes after sauna; 6 = at the end of 30 min recovery after sauna). All participants underwent the recommended sauna protocol successfully. Participants remained in a seated upright position during the sauna and for the measurements. Immediately after sauna exposure, participants were instructed to have a relaxing rest in a designated waiting lounge (mean temperature 21°C) for 30 minutes.

2) I also remain unconvinced that the changes in HR and HRV can be attributed to sauna bathing itself:

- Without a control period, it cannot be ruled out that simply getting up and walking to/from the sauna caused the observed changes in HR and HRV during the post-sauna period. This limitation needs to be better recognized in the discussion. The authors state that the single-group design is appropriate "given the pilot experimental nature of the novel study and limited funding available" (P. 15). The study design should be justified based on whether it can adequately answer the research question. It should not be justified based on resource or budget limitations.

RE: Thank you very much for your suggestions. We have discussed that it may be possible that the observed changes from pre- to post-sauna were due to a lack of standardized measurements before sauna and not due to sauna itself and we acknowledge this in the revised version of our manuscript (on page 15). However, this is best we can do with this kind of experiments at the moment. We have emphasized that this was one of the first studies in this field. In future studies, it may be possible to develop more sophisticated protocols using a more controlled design. On the other hand, in conducting this study in conditions similar as people normally use sauna increases the potential relevance and implications of our data. All participants were asked to

remain seated both before and after sauna when HRV and HR were recorded using the heart rate monitoring device.

We have added in the discussion that the lack of a comprehensive control period limits the interpretation of the data on HR and HRV before and after sauna (on page 15). Without a time-control period, it cannot be determined if the observed changes can be directly attributed to sauna, or simply to changes over time. Therefore, as mentioned above, more studies are needed.

- Without providing repeatability of the HR and HRV measures, it cannot be determined if the observed changes are greater than measurement error. What is the repeatability for these measures when performed in your laboratory?

RE: We totally agree with this concern. This is the first study on this topic. This question is also related to the absence of control group, whose presence would help clarify this point. We did not directly test the repeatability of the measures but the manufacturer indicates that the device is acceptable for this kind of field studies like the assessment of HR during the exercise and/or sauna. Moreover, previous studies have been using the same Polar V800 monitor that measures RR interval with a 1 ms resolution. If interferences - artifact movement and major and complex or frequent arrhythmias are excluded (our participants were medically evaluated and were resting during these measurements) -, HR and derived-HRV measurements performed by this transmitter-monitor system have been systematically reported as highly reliable and valid.

On page 8, we have written that previous findings show the validity of the Polar V800 and its ability to produce RR interval recordings consistent with an ECG, and HRV variables derived from these recordings are also highly comparable (Giles D, Draper N, Neil W. Validity of the Polar V800 heart rate monitor to measure RR intervals at rest. *Eur J Appl Physiol* Mar 2016;116:563-571). As we have mentioned in the text HR and HRV measurements were carried out by using a RR-interval data obtained by a Polar V800 HR monitor and analyzed by the specific Kubios software (Tarvainen MP, Niskanen JP, Lipponen JA, Ranta-Aho PO, Karjalainen PA. Kubios HRV--heart rate variability analysis software. *Comput Methods Programs Biomed* 2014;113:210-220).

For this study, a large number of RR-intervals were quantified for several minutes and then considered, in order to minimize interferences and to obtain data amenable to HRV adequate measurements and calculations in both time and frequency-domains. We had strict time control between HR and HRV measurements, as we have reported in the methods.

3) P. 15: Please explain how HR and HRV provide "distinct indices of cardiac autonomic function"? Changes in sympathetic/parasympathetic activity will necessarily result in heart rate changes. Therefore, how can one be dissociated from the other? The authors cannot dismiss the possibility that the change in HRV simply reflect the change in HR. This is a well-recognized limitation of HRV measures (PMID: 31006856). HRV data can and should be corrected for HR (see PMID: 23986716, 24602150, 25225208). This correction is important to ensure adequate interpretation of the HRV data.

RE: Thank you very much for this comment which drove us to investigate in more detail previous data about the inter-dependence between HRV and HR. The Hypertension paper (25225208), in particular, also reports a possible non-linear (exponential decay-like) equation to estimate numerically HRV accounting for HR (formula 8). We also note that this is an old debate and some contrary ideas have also been reported (i.e., there are scale-free HRV indices which do not need "normalisation"; 28264918).

In the revised paper, we have highlighted these points underlying the relationship between HRV and HR and re-phrased the sentence (on page 15): "However, our study evaluated both HRV and HR, which are two distinct indices of cardiac autonomic function. On the other hand, there are studies indicating that we should not underestimate the possibility that the change in HRV reflect the change in HR. Due to the inverse curvilinear relationship between HR and R-R interval, HR per se can

profoundly influence HRV parameters. Some authors have suggested that HRV is dependent on HR and cannot be used in a simple way to assess autonomic function."

We have reported the changes in HR, but we have not adjusted for it. HR and HRV are highly correlated which must be taken into account in all analyses with regard to HR and HRV. As the reviewer has suggested, we have also added the following new references and additional discussion on this topic (on page 15):

On the other hand, there are studies indicating that we should not underestimate the possibility that the change in HRV simply reflect the change in HR. Due to the inverse curvilinear relationship between HR and R-R interval, HR per se can profoundly influence HRV parameters. Some authors have also suggested that HRV is dependent on HR and cannot be used in a simple way to assess autonomic function.

Boyett M, Wang Y, D'Souza A: CrossTalk opposing view: Heart rate variability as a measure of cardiac autonomic responsiveness is fundamentally flawed. *J Physiol.* 2019 May;597(10):2599-2601.

Billman GE: The effect of heart rate on the heart rate variability response to autonomic interventions. *Front Physiol.* 2013 Aug 26;4:222.

Sacha J. Interaction between heart rate and heart rate variability. *Ann Noninvasive Electrocardiol.* 2014 May;19(3):207-16.

Monfredi O, Lyashkov AE, Johnsen AB, Inada S, Schneider H, Wang R, Nirmalan M, Wisloff U, Maltsev VA, Lakatta EG, Zhang H, Boyett MR. Biophysical characterization of the underappreciated and important relationship between heart rate variability and heart rate. *Hypertension.* 2014 Dec;64(6):1334-43.

4) I am still unsure why t-tests were performed in addition to the ANOVA model to evaluate pre to post changes in HR and HRV. A post-hoc analysis from the ANOVA can compare the pre to post changes, without the need for separate t-tests. I am concerned that multiple t-tests increases the rate of type I error. Was a correction applied for multiple comparisons?

RE: We totally agree with the reviewer's concern about multiple testing and type I error. In our study, about multiple adjustment, we did not perform any correction. In fact, as in both differences we used time 1 as reference, this is conceptually and analytically corresponding to a regression (i.e. difference) whereby time 1 is used as reference and all others are compared to time 1. Before and after sauna exposure data comparisons were analyzed for within-group changes with a paired t-test.

5) The study by Radtke et al. (PMID: 26152773) needs to be integrated to the discussion of previous studies which examined the acute effect of sauna bathing on HRV.

RE: Thank you very much, we have now added the reference: Radtke T, Poerschke D, Wilhelm M, Trachsel LD, Tschanz H, Matter F, Jauslin D, Saner H, Schmid JP. Acute effects of Finnish sauna and cold-water immersion on haemodynamic variables and autonomic nervous system activity in patients with heart failure. *Eur J Prev Cardiol.* 2016 Apr;23(6):593-601.

6) The method for measuring humidity within the sauna is still missing.

RE: It was measured by a humidity meter (Harvia Co.), where all the experiments were conducted. This information is now included in the revised version.

7) The make/model of the tympanic thermometer is not provided.

RE: We used Apteq RA600 tympanic thermometer (Apteq RA600, Rossmax International Ltd Rossmax Swiss GmbH). This has been added.

We have added new important references and organized the reference list accordingly.

Revision 2

Recovery from sauna bathing favorably modulates cardiac autonomic nervous system

Running title: Sauna and heart rate variability

Tanjaniina Laukkanen ^{a,b}, Jukka Lipponen ^c, Setor K. Kunutsor ^{d,e}, Francesco Zaccardi ^f, Claudio Gil S. Araújo ^g, Timo H. Mäkikallio ^h, Hassan Khan ⁱ, Peter Willeit ^j, Earric Lee ^k, Sanna Poikonen ^l, Mika Tarvainen ^c, Jari A. Laukkanen ^{a,b,k}

^aInstitute of Public Health and Clinical Nutrition, University of Eastern Finland, Kuopio, Finland

^bCentral Finland Health Care District, Department of Internal Medicine, Jyväskylä, Finland

^cDepartment of Applied Physics, University of Eastern Finland, Kuopio, Finland

^dNational Institute for Health Research Bristol Biomedical Research Centre, University Hospitals Bristol NHS Foundation Trust and University of Bristol, Bristol, UK

^eMusculoskeletal Research Unit, Translational Health Sciences, Bristol Medical School, University of Bristol, Learning & Research Building (Level 1), Southmead Hospital, Bristol, UK

^fDiabetes Research Centre, Leicester General Hospital, University of Leicester, Leicester, UK

^gExercise Medicine Clinic;CLINIMEX, Rio de Janeiro, RJ, Brazil

^hDivision of Cardiology, Department of Internal Medicine, Oulu University Hospital, Oulu, Finland

ⁱDepartment of Medicine, Division of Cardiology, Emory University, Atlanta, GA, US

^jDepartment of Neurology, Medical University Innsbruck, Innsbruck, Austria

^kFaculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland

^lPihlajalinna Clinic, Jyväskylä, Finland

Address for Correspondence:

Jari A. Laukkanen, Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland P.O. Box 35, 40014 Jyväskylä, Finland, tel:+358408053478, E-mail: jari.a.laukkanen@jyu.fi

Words ~~4256~~119

Abstract

Objective: Sauna bathing is becoming a common activity in many countries and it has been linked to favorable health outcomes. However, there is limited data on the heart rate (HR) and heart rate variability (HRV) responses to an acute sauna exposure.

Design: We conducted a single-group, time series longitudinal study utilizing a pre-post design to examine acute effects of sauna bathing on the autonomic nervous system as reflected by HRV. A total of 93 participants (mean [SD] age: 52.0 [8.8] years, 53.8% males) with cardiovascular risk factors were exposed to a single sauna session (duration: 30 minutes; temperature: 73°C; humidity: 10-20%) and data on HRV variables were collected before, during and after sauna.

Results: Time and frequency-domain HRV variables were significantly modified ($p < 0.001$) by the single sauna session, with most of HRV variables tending to return near to baseline values after 30 minutes recovery. Resting heart rate was lower at the end of recovery (68/min) compared to pre-sauna (77/min). A sauna session transiently diminished the vagal component, whereas the cooling down period after sauna decreased low frequency power ($p < 0.001$) and increased high frequency power in HRV ($p < 0.001$), favorably modulating the autonomic nervous system balance.

Conclusions: This study demonstrates that a session of sauna bathing induces an increase in heart rate. During the cooling down period from sauna bathing, HRV increased which indicates the dominant role of parasympathetic activity and decreased sympathetic activity of cardiac autonomic nervous system. Future randomized controlled studies are needed to show if HR and HRV changes underpins the long-term cardiovascular effects induced by regular sauna bathing.

Keywords: sauna bathing, heat therapy, heart rate variability, cardiovascular response

1. Introduction

Emerging evidence suggests that sauna bathing, a passive form of heat therapy, has several health benefits.¹ Regular sauna bathing has beneficial effects on the cardiovascular system and which include improved endothelial and microvascular function and reduced arterial stiffness and blood pressure.²⁻⁵ Consistent with these observations, it has been shown that frequent sauna bathing is associated with a reduced risk of dementia,⁶ fatal cardiovascular outcomes and all-cause mortality.⁷ Sauna may favorably modulate the autonomic nervous system, which is a contributing risk factor for cardiovascular disease (CVD).⁸⁻¹⁰ There is a broad body of evidence on the association between cardiac autonomic nervous dysfunction and the risk of fatal arrhythmias.¹¹⁻¹² Regular sauna bathing has been postulated to exert a potential therapeutic effect on blood pressure¹³ which may be partly explained via favorable effects on cardiac autonomic nervous system balance.

Heart rate variability (HRV) is a marker of autonomic nervous system balance, which is a measure of heart rate (HR) fluctuations around the mean HR and has been used to indicate the balance between parasympathetic and sympathetic function of the autonomic nervous system. Higher HRV is indicative of a greater capacity of the cardiovascular system to respond to changes in stressful conditions.¹⁴ A reduced HRV is associated with an increased risk for hypertension, CVD, sudden cardiac death (SCD), and cardiac arrhythmias;^{8,15-17} indeed, autonomic nervous system imbalance with an increased sympathetic or reduced vagal tone has been implicated in the pathophysiology of SCD.^{11,18} HRV analysis provides additional insight into cardiovascular responses to heat exposure. It has been suggested that endurance exercise training and many other physical activities may increase vagal activity and decrease sympathetic activity at rest and recovery.¹⁹⁻²¹ There is evidence to suggest that relaxation techniques may increase HRV.²² Sauna bathing, a common life-style habit used mainly for relaxation and pleasure purposes to release body stress,^{23,24} may have effects on parasympathetic activity of the autonomic nervous system.

Sauna bathing leads to an increase in HR,²⁵ thereby imitating moderate physical activity and its possible effects on autonomic nervous system without active skeletal muscle work. Additionally, it is known that the acute physiological responses to high temperatures during sauna bathing induces fluid loss with an increase in HR.^{25,26} Evidence also suggests that exposure to high ambient temperature is associated with an increase in HRV.²⁷ A number of studies have shown that other passive heat therapies (eg. infrared-ray sauna, Waon therapy, etc) improve cardiac function and autonomic nervous activity in patients with pre-existing conditions such as heart failure and chronic respiratory disease.²⁹⁻³⁰ There is however very limited data on the effects of typical Finnish sauna bathing on autonomic nervous system indices such as HRV in participants with cardiovascular risk factors. Given the overall evidence, we hypothesized that immediately after a single sauna exposure, it is possible to identify favorable cardiac autonomic responses. In this context, we conducted an experimental study to investigate cardiac autonomic nervous system responses, by using HRV measurements, during and immediately after sauna bathing among participant with at least one cardiovascular risk factor.

2. Methods

2.1. Participants

This study was part of the sauna and cardiovascular health study, which has been described in previous reports.^{4,5} Participants (n=93) were recruited from the city of Jyväskylä, Central Finland region, through the local out-of-hospital health care center. The study group consisted of participants without symptomatic CVD who had at least one cardiovascular risk factor, such as a history of smoking, dyslipidemia, hypertension, obesity, diabetes, or family history of coronary heart disease (CHD). Participants with diagnosed CVD were not included in the study. Prior to the participation of the study, all participants were informed about the

research purposes, measurement procedures, and were interviewed and examined by a cardiologist.

The investigation was concordant with the principles outlined in the Declaration of Helsinki and its future amendments. The research protocol and study design were reviewed and approved by the institutional review board of the Central Finland Hospital District ethical committee, Jyväskylä, Finland (Dnro 5U/2016). All participants provided written informed consent.

2.2. Clinical examination

A clinical evaluation with baseline data collection was conducted on a separate day prior to the actual sauna experiment. During the screening visit, medical history, physical examination, and resting electrocardiogram (ECG) were assessed. All baseline and sauna measurements were performed from May to June 2016, as a part of the sauna and cardiovascular health study.⁴ Resting blood pressure was measured as the mean of two measurements, obtained while the participant was supine with a standardized measurement protocol. Body mass index (BMI) was calculated by dividing measured weight in kilograms by the square of height in meters. Assessment of baseline characteristics and diseases were based on a self-reported questionnaire which was checked by a cardiologist during the screening visit. The regular use of medication was assessed by a detailed questionnaire. All questionnaires have been previously validated in a Finnish population-based cohort study.³¹

2.3. Assessment of sauna bathing habits

Previous regular sauna bathing habits were assessed by the questionnaires and the information collected was based on frequency (weekly sauna sessions), duration of sauna exposure, and temperature of the sauna during the exposure. The questionnaires were cross-checked at the time of baseline data collection.

2.4. Sauna exposure

Sauna exposure was based on dry air and relatively high temperature.⁷ Sauna exposure was a typical Finnish sauna bathing session; the total duration was 30 minutes, and it was divided into two 15 minutes sessions with a short, two-minute warm (temperature of 38°C) shower in-between the sessions. The given sauna protocol is applicable for our study population with regard to safety issues and it also corresponds very well with typical sauna use in Finland.

The sauna rooms were gender specific. The temperature and humidity ~~were~~ measured continuously by using a 2-channel thermometer in the sauna room (Harvia Co Oy, Finland) and the respective data was collected during the entire experiment. The temperature of sauna was measured at 10 seconds intervals during the sauna sessions. Data obtained via the temperature tracking device showed that the mean temperature was 73 (standard deviation, SD ± 2) °C with a relative humidity of 10-20%.⁴

Experiments were supervised by a physician and participants were given the opportunity to leave the sauna at any time they felt uncomfortable. All participants underwent the recommended sauna protocol successfully. Participants remained in a seated upright position. Immediately after sauna exposure, participants were instructed to rest in a designated relaxing waiting lounge (mean temperature 21°C) for 30 minutes' recovery. To make up for fluid loss due to increased sweating, participants were given 500 mL still water at room temperature for drinking during the entire sauna session, including the recovery period after sauna.^{4,25,256}

Body temperature was measured for each participant by the tympanic method (Apteq RA600, Rossmax International Ltd Rossmax Swiss GmbH).

2.5. Assessment of heart rate and heart rate variability

HR and HRV data were collected by a Polar V800 monitor (Polar, Finland), using a chest strap transmitter. Previous findings have shown~~support~~ the validity of the Polar V800 and its ability to produce RR interval recordings consistent with an ECG, and HRV variables derived

from these recordings are also highly comparable.³² Raw HR data was analysed by Kubios HRV system (version 3.0.2),³³ which is an advanced software for HRV analysis. The software computes all the commonly used time-domain and frequency-domain HRV and several nonlinear variables based on beat-to-beat RR interval data.³³

In addition to detailed HR data collection in sauna, the following HRV variables - mean RR interval, root mean square of the successive differences between RR intervals (RMSSD), standard deviation of normal RR intervals (STDRR), low frequency (LF) power, high frequency (HF) power, total power, LF power normalized (nu) and HF power nu - were collected from six different assessment times with the participants placed at stable sitting position before, during and after the sauna exposure (time 1 = before sauna; 2 = 5-10 minutes in sauna; 3 = 15-20 minutes in sauna; 4 = 25-30 minutes in sauna; 5 = 2-7 minutes after sauna; 6 = at the end of 30 min recovery after sauna). These assessment points represent HR and HRV changes from pre-sauna to in-sauna phase until the end of recovery period post sauna allowing us to investigate HR and HRV profile during and in the 30-minute period after a single sauna bathing session. Participants were seated at least 10 minutes in the chair in the quiet lounge room before and after sauna when HR and HRV data was collected. FFT was used for the spectrum estimation. Bandwidths was LF 0.04-0.15 and HF 0.15-0.4. LF and HF powers were expressed both in absolute values (ms^2) and in normalized values (nu). The normalisation of LF and HF was performed by subtracting the very low frequency component (VLF) from the total power. LF and HF were normalized by calculating $\text{LF}/(\text{TP}-\text{VLF}) \times 100$ and $\text{HF}/(\text{TP}-\text{VLF}) \times 100$, respectively, to receive values independent of total power. This procedure reduces the effects of noise due to artifacts and minimizes the effects of the changes in total power on the LF and HF components. RR interval, RMSSD, STDRR were measured in milliseconds (ms) whereas total power, LF and HF were measured in ms^2 .

2.6. Exercise testing

To assess and confirm potential safety issues in our participants with cardiovascular risk factors before sauna exposure, a graded maximal standard clinical (ECG monitoring) exercise test was conducted on a cycle ergometer and the level of cardiorespiratory (aerobic) fitness was assessed.⁴ The exercise test with continuous ECG (CardioSoft software V.1.84, GE Healthcare, Freiburg, Germany) recordings was performed at baseline visit using an electrically braked cycle ergometer (Monark Exercise AB, Sweden). The test was started with 3 minutes' warm-up with no resistance added and continued with 20-watt increments applied each 1 min until volitional exhaustion. Cardiorespiratory fitness was expressed in metabolic equivalents (METs) and maximal exercise workload in watts-. All exercise tests were supervised by an experienced physician with the assistance of a trained nurse and were not performed on the same day of sauna session.⁴

2.7. Laboratory analyses

Venous blood samples for the determination of plasma total, high-density lipoprotein (HDL) and low-density lipoprotein (LDL) cholesterol, triglycerides (TG) and plasma glucose concentrations were collected by a qualified laboratory technician from the antecubital vein, into serum and plasma tubes (BD Vacutainer, Plymouth, UK). These analyses were taken to define cardiometabolic risk factor profile on the day participants were screened. All other blood samples for other analyses were taken on the day of the sauna experiment.⁴ Participants were instructed to abstain from strenuous physical activity and sauna use 24h before the blood samples were taken. Whole blood samples were stored for 10 min before being centrifuged at 3500 rpm (Megafuge, Heraeus, Germany) and serum and plasma samples stored at -80°C until analysis using a spectrophotometry analyzer (Konelab 20XTi, Thermo Fisher Scientific, Vantaa, Finland). Venous blood samples for the determination of plasma biomarkers including hs-C-reactive protein and plasma creatinine were analyzed using

chemiluminescent immunoassay by Siemens Immulite 2000 XPi analyzer (Siemens Healthcare Diagnostics Products Ltd., Llanberies, UK).

2.8. Statistical analyses

Data are presented as means (SDs) or median (interquartile range) for continuous variables according to their distribution and as number (proportions) for categorical variables.

Normality was checked using the Shapiro-Wilk test as well as through observing the Q-Q-plots. Differences of normally distributed and log-transformed non-normally distributed HRV variables before (time 1), during (times 2, 3, 4) and after (times 5,6) sauna were estimated using repeated measures mixed models with an independent covariance. Before sauna exposure and during the recovery after sauna exposure data were analysed for within-group changes with a paired t-test. To investigate possible effects of sauna bathing on autonomic nervous balance during recovery (e.g. changes in parasympathetic activity), we compared HR and HRV before sauna (time 1) to the two assessment points at the recovery phase (time 5 and 6), both of which were defined as after the sauna. Both absolute and relative changes in HR and HRV analyses were performed. The associations between HR responses during sauna with cardiorespiratory fitness, age and BMI were analyzed. The level for significance was set at $p < 0.05$. All statistical analyses were carried out with Stata version 14.1 (Stata Corp, College Station, Texas, U.S.) and results are reported with 95% confidence intervals.

3. Results

The mean (SD) age, BMI, and cardiorespiratory fitness of the participants included in this study were 52.0 (8.8) years, 27.5 (4.5) kg/m², and 9.0 (2.1) METs, respectively. Proportion of current smokers was 14.4% and the resting systolic blood pressure and diastolic blood pressure were 137 (17) and 82 (10) mmHg, respectively. The proportion of participants with

hypertension was relatively low (15.4%); hyperlipidemia and a family history of CHD were common cardiovascular risk factors in the study population (**Table 1**). The majority of participants reported using sauna baths 3 times per week (47.3%); the proportion of those using sauna 1 or 2 times per week was 15.4%. Other characteristics of study's participants are shown in **Table 1**.

Mean temperature of sauna room was 72°C. None of the participants demanded to leave the sauna room before the 30-minute sauna exposure period and no adverse events occurred. Mean body temperature increased during sauna session and tended to return to pre-sauna values at the end of 30-minute period after sauna - 36.4 (0.5) °C before sauna, 38.4 (0.7) °C immediately after sauna and 36.6 (0.4) °C at recovery ($p < 0.001$) -. Sauna exposure was associated with a statistically significant increase in HR. HR and RMSSD profiles along the six measurements performed in the study are shown in **Figure 1a** and **b**, respectively. Mean HR increased from pre-sauna 77 beats per minute (time 1) to 120 per minute values (time 4). Immediately after sauna, mean HR was 83 beats per minute (time 5), decreasing to 68 beats per minute (time 6) at the end of recovery phase as reported in **Table 2**. Relative changes in HR, compared to baseline, are presented in **Supplementary Figure 1**.

Sauna bathing had significant effects on HRV variables as shown in **Table 2** and **Figure 2**. In addition to HR changes, mean RR interval, RMSSD, STDRR, LF, HF and total power were also changed when comparing pre-sauna values to immediate post sauna and post-30 min after sauna (**Table 2**). Mean RR was significantly higher post 30-min minutes after sauna as compared to pre-sauna levels. When comparing pre-sauna HRV variables to immediately after sauna or after 30 minutes recovery, most of HRV variables changed significantly. The reduction in LF power was -38.3% from pre-sauna to the end of recovery with a parallel increase in HF power of 27.8% (**Table 2**). In addition to total power change, normalized LF (20%) and HF (67 %) power changed significant ($p < 0.001$) from pre-sauna until the end of recovery.

Supplementary Figure 2 shows the relationship of the difference between maximum HR response during sauna vs individual-level characteristics including maximal HR, cardiorespiratory fitness, age and BMI. The greater the levels of maximum exercise test, the lower the maximum HR level during sauna (up to 50% smaller in participants with maximum exercise HR of around 190-200 bpm). There were no significant associations between the magnitude of HR response during sauna and levels of cardiorespiratory fitness, age or BMI (**Supplementary Figure 2**).

4. Discussion

This single-group time series study investigated the effects of sauna bathing on HR and HRV ~~variables~~ parameters in adults with risk factors but without diagnosed CVD. The results from this study showed that a single sauna exposure leads to significant changes in cardiac autonomic nervous balance as indicated by changes in the HRV variables, including RMSSD, STDRR, LF, HF, and total power. HRV was favorably modulated after 30 minutes sauna exposure, suggesting a potential beneficial cardiovascular effect and a stress-releasing effect of sauna bathing during the recovery period.

These new results on sauna and HRV are in line with recent population-based study findings which indicate sauna bathing to be associated with reduced risk of CVDs.^{1,7,13} Evidence on the role of Finnish sauna bathing on HRV is very limited, and thus this study provides novel findings on the effects of sauna bathing on autonomic nervous system modulation. Previous evidence on the beneficial effects of sauna on the autonomic nervous system have been based on the long-term effects of other passive heat therapies such as infrared-ray sauna and Waon therapy employed in patients with pre-existing conditions such as chronic heart failure (CHF). In a randomised control trial (RCT) of 4 weeks of Waon therapy versus usual care in patients with CHF, Waon therapy was demonstrated to have beneficial effects on several indices of the autonomic nervous system.²⁸ In another RCT of infrared-ray dry sauna versus

no sauna treatment in patients with CHF, HRV was increased after 5 weeks of sauna treatment.²⁹ Six weeks of Thai sauna treatment in patients with allergic rhinitis led to significant changes in HRV.³⁰

In contrast to these studies, our findings were based on a 30 minute exposure to Finnish sauna in participants with at least one cardiovascular risk factor with no pre-existing history of CVD. It has been shown that LF/HF ratio was increased after the sauna exposure in normal control subjects and patients with coronary artery disease.³⁴ ~~It has been previously reported that a~~ single sauna session may induced a significant alteration of autonomic cardiovascular control in patients with untreated hypertension who generally experience, ~~with an~~ increased sympathetic and decreased parasympathetic activity.³⁵⁴ These changes positive alterations in cardiac autonomic nervous system were largely recovered ~~normalized~~ within a period of 15 to 120 minutes after sauna bathing.³⁵⁴ Another study suggested that post-exercise sauna exposure caused mild to moderate changes in resting vagal related HRV.¹⁰ HR response to heat stress is considered to be similar to the physiological cardiovascular response to physical exercise, which may further influence favorably on HRV and cardiac autonomic nervous system. Even mild heat stress has been shown to influence main components of HRV, leading to a reduced HF component and increased LF/HF ratio within minutes of heat exposure.³⁶⁵ In the current study, HRV was lowered during heat exposure, whereas HRV-HF activity, as an indicator of modulation in vagal activity, was substantially increased during the recovery (cooling down) phase from sauna.

This study showed that sauna bathing leads to significant modulation in cardiac autonomic nervous balance including increased parasympathetic activity after sauna bathing as indicated by changes in the balance of RMSSD, STDRR, LF and HF power, and HRV total power variables. High frequency power and HF-power nu increased while LF-power with LF-power nu decreased, which potentially affects favorably on the cardiac autonomic nervous system by increasing vagal tone activity in the 30-minute after sauna period. Increased sweating during sauna bathing is accompanied by reduction in blood pressure and a higher HR, whilst

cardiac stroke volume is largely maintained; although a part of blood volume is diverted from the internal organs to peripheral body parts with decreasing venous return which is not facilitated by active skeletal muscle work. Indeed, comparable with exercise-induced adaptations, heat stress could increase HR up to 150 per minute.²⁶ Exposure to a Finnish sauna bath with an intensive thermal stimulus has been shown to increase HR with a corresponding decrease in HF-HRV component.³⁷⁶ Our study showed that [the mean](#) HR increased from 77 beats per minute to 120 per beats minute level, while the highest observed HR of a participant was 150 per minute. Heart rate increased gradually from the beginning of sauna bath until the end, corresponding with an increase in body temperature.

It has been previously proven that hypertension, malignant arrhythmias, coronary artery disease and acute myocardial infarction are associated with a reduction of HRV.^{11,387} Regular physical exercise, perhaps in combination with sauna bathing, is a potential preventive strategy to favorably increase HRV in population, most probably by inducing larger increases in cardiac vagal activity.^{19,20} Regular sauna bathing has been shown to decrease risk of cardiovascular outcomes such as hypertension, fatal CVD events, SCD and neurodegenerative diseases.^{6,7,13} Then, it is highly possible that the benefits of sauna bathing may be partly explained via effects of improved cardiac autonomic nervous system balance.¹ Also, our current study shows an inverse relationship between maximal HR during exercise and HR response to sauna: participants with lower HR levels during maximal exercise test achieved higher HR responses during sauna. It is interesting to note that sauna bathing may increase HR to the level which corresponds with moderate intensity of exercise.

In this study, HRV was measured to detect the modifications in sympatho-vagal activity during (at 73°C degrees) and after sauna (at 21°C degrees) using a common Finnish sauna protocol. The temperature of sauna was stabilized and controlled for every participant and measured at 10 seconds intervals during the sauna sessions. Participants' body temperature increased from the mean level of 36.4°C to 38.4°C immediately after sauna, although body temperature tended to decrease during the 30 minutes recovery period at a normal room

temperature back to individual pre-sauna temperature levels. The positive effects on the autonomic nervous system were based on traditional hot and dry Finnish sauna bathing, which is unlike other types of saunas operating at lower temperatures or heated water immersion.^{2,3} As this is the first study showing acute effects of 30 minutes' sauna exposure imitating a typical sauna session with a short 1-2 minutes 38°C shower combined with 30 minutes recovery period among participants with risk factors, we focused only on immediate effects of sauna bathing on body heat physiology, HR and HRV. However, it is unclear if sauna bathing induced changes in plasma volume might have effect on HRV responses.^{389,4039}

Among athletes, acute exposure to extreme heat stress via sauna produced alterations in heart rate and cardiac autonomic modulations, with increased RMSSD during a sauna session.⁴¹³⁹

Our current study is based on a relatively large number of participants, which provided adequate power to assess changes in HRV variables. In this study, the assessment of HR and HRV were performed using standard measurement protocols using HRV analysis system.³³

The limitations of this study deserve consideration. First, our study was based on a single group intervention pre-post design (without a control group or crossover design), which obviously has limitations compared to RCTs. The lack of a comprehensive control period limits the interpretation of the data on HR and HRV results before and after sauna based on changes over time. However, given the pilot experimental nature of the novel study and limited funding available, we considered this design appropriate. Second, we were unable to adjust HRV for HR values, given that it is well established that measures of HRV are nonlinearly dependent on HR.^{402,413} Indeed, it has been suggested that HRV should not be used alone to assess autonomic nervous system activity.^{354,4039} However, our study evaluated both HRV and HR, which are two distinct indices of cardiac autonomic function. On the other hand, there are studies indicating that we should not underestimate the possibility that the change in HRV reflect the change in HR. Due to the inverse curvilinear relationship between HR and R-R interval, HR per se can profoundly influence HRV parameters.⁴⁴ Some authors have also suggested that HRV is dependent on HR and cannot be used in a simple

[way to assess autonomic function.](#)⁴⁵ -Third, our HRV measurements were not collected with paced breathing and we could not collect any measurements on breathing. We had no respiratory rate data available before, during or after the sauna bathing, which may partly limit our interpretation with regards to vagal tone changes. Fourth, it would have been appropriate to adjust fluid intake by assessing fluid loss using body weight before and after sauna exposure, however, we aimed to test traditional Finnish sauna habits. Fifth, the intervention was relatively short-term without serial repeated HRV measurements during a longer recovery period. The study design is, however, novel in this context focusing on immediate acute effects of sauna bathing on cardiac autonomic nervous system function. Findings from a previous epidemiological study suggest that to reduce CVD risk, frequent and regular sauna sessions of at least 20 minutes in duration for a single session may be required to exhibit beneficial effects on cardiovascular function.^{1,7} We focused on population with cardiovascular risk factors as they might benefit from lifestyle interventions. The most beneficial duration of sauna has to be defined and as to whether combining a sauna bathing session with physical activity may be more effective with respect to changes in autonomic nervous system balance needs exploration. Indeed, we have previously shown that a combination of good cardiorespiratory fitness levels produced by aerobic exercise and frequent sauna bathing confer more protection on the risk of cardiovascular and all-cause mortality.^{46-48,43} Finally, given that sauna bathing is a traditional habit in Finland, all our study participants were regular sauna users (minimum of one sauna session per week) as it was virtually impossible to recruit sauna naïve participants. Findings may therefore be confounded and not be generalizable to other populations that are not familiar with sauna bathing.^{1,32,33}

This study showed the acute effects of a typical Finnish sauna on HR and HRV in a population with cardiovascular risk factors [among regular sauna bathers](#). The results indicate that sauna bathing improves cardiac autonomic nervous system balance, leading to increase in vagal tone and decrease in sympathetic tone, with favorable modulations in HRV variables

during the recovery from sauna. We found that a single sauna exposure leads to significant changes in cardiac autonomic nervous balance as indicated by modulation in the parameters of HRV such as RMSSD, STDRR, LF, HF, and total power. Sauna bathing is a recommendable habit for relaxation, although additional studies are warranted to establish the potential mid- and longer-term effects of sauna bathing on positive autonomic nervous system adaptations. On the basis of this study, HRV was modulated after 30 minutes sauna exposure, suggesting a stress-releasing effect of sauna bathing during the recovery period.

Acknowledgements

This study was supported by the Finnish Funding Agency for Technology and Innovation, Helsinki, Finland.

Conflict of Interest

The authors declare that there are no competing interests.

Figure Legends

Figure 1. Changes in heart rate during and after sauna bathing (a) and changes in root mean square of the successive differences (RMSSD) between RR intervals during and after sauna bathing (b)

Figure 2. Heart rate variability parameters change during and after sauna bathing

References

1. Laukkanen JA, Laukkanen T, Kunutsor SK. Cardiovascular and other health benefits of sauna bathing: A review of evidence. *Mayo Clinic Proceedings*. 2018 93:1111-1121.
2. Brunt VE, Eymann TM, Francisco MA, Howard MJ, Minson CT. Passive heat therapy improves cutaneous microvascular function in sedentary humans via improved nitric oxide-dependent dilation. *J Appl Physiol* (1985). 2016;121:716-723.
3. Brunt VE, Howard MJ, Francisco MA, Ely BR, Minson CT. Passive heat therapy improves endothelial function, arterial stiffness and blood pressure in sedentary humans. *J Physiol Sep* 2016;594:5329-5342.
4. Laukkanen T, Kunutsor SK, Zaccardi F, Lee E, Willeit P, Laukkanen JA. Acute effects of sauna bathing on cardiovascular function. *J Hum Hypertens*. 2018;32:129-138
5. Lee E, Laukkanen T, Kunutsor SK, et al. Sauna exposure leads to improved arterial compliance: Findings from a non-randomised experimental study. *Eur J Prev Cardiol*. 2018;25:130-138
6. Laukkanen T, Kunutsor S, Kauhanen J, Laukkanen JA. Sauna bathing is inversely associated with dementia and Alzheimer's disease in middle-aged Finnish men. *Age Ageing*. 2017;46:245-249.
7. Laukkanen T, Khan H, Zaccardi F, Laukkanen JA. Association between sauna bathing and fatal cardiovascular and all-cause mortality events. *JAMA Internal Medicine*. 2015;175:542-548.
8. Hillebrand S, Gast KB, de Mutsert R, et al. Heart rate variability and first cardiovascular event in populations without known cardiovascular disease: meta-analysis and dose-response meta-regression. *Europace*. 2013;15:742-749.
9. Lietava J, Vohnout B, Valent D, Celko J. Comparison of hemodynamics during hyperthermal immersion and exercise testing in apparently healthy females aged 50-60 years. *Ital Heart J*. 2004;5:511-516.
10. Stanley J, Halliday A, D'Auria S, Buchheit M, Leicht AS. Effect of sauna-based heat acclimation on plasma volume and heart rate variability. *Eur J Appl Physiol*. 2015;115:785-794.
11. Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *Eur Heart J*. 1996;17:354-381.
12. Sztajzel J. Heart rate variability: a noninvasive electrocardiographic method to measure the autonomic nervous system. *Swiss Med Wkly*. 2004;134:514-522.
13. Zaccardi F, Laukkanen T, Willeit P, Kunutsor SK, Kauhanen J, Laukkanen JA. Sauna bathing and incident hypertension: A prospective cohort study. *Am J Hypertens*. 2017;30:1120-1125.
14. Fiorelli A, Messina G, Chiodini P, et al. Cardiac Autonomic Changes After Thoracic Sympathectomy: A Prospective, Randomized Study. *Ann Thorac Surg*. 2017;103:216-224.
15. Singh JP, Larson MG, Tsuji H, Evans JC, O'Donnell CJ, Levy D. Reduced heart rate variability and new-onset hypertension: insights into pathogenesis of hypertension: the Framingham Heart Study. *Hypertension*. 1998;32:293-297.

16. La Rovere MT, Pinna GD, Maestri R, et al. Short-term heart rate variability strongly predicts sudden cardiac death in chronic heart failure patients. *Circulation*. 2003;107:565-570.
17. Meyerfeldt U, Wessel N, Schutt H, et al. Heart rate variability before the onset of ventricular tachycardia: differences between slow and fast arrhythmias. *Int J Cardiol* Aug 2002;84:141-151.
18. Maheshwari A, Norby FL, Soliman EZ, et al. Low heart rate variability in a 2-minute electrocardiogram recording Is associated with an increased risk of sudden cardiac death in the general population: The Atherosclerosis Risk in Communities Study. *PLoS One*. 2016;11:e0161648.
19. Murad K, Brubaker PH, Fitzgerald DM, et al. Exercise training improves heart rate variability in older patients with heart failure: a randomized, controlled, single-blinded trial. *Congest Heart Fail* 2012 Jul-Aug 2012;18:192-197.
20. Routledge FS, Campbell TS, McFetridge-Durdle JA, Bacon SL. Improvements in heart rate variability with exercise therapy. *Can J Cardiol*. 2010;26:303-312.
21. Messina G, Vicidomini C, Viggiano A, et al. Enhanced parasympathetic activity of sportive women is paradoxically associated to enhanced resting energy expenditure. *Autonomic Neuroscience: Basic and Clinical*. 2012;169:102-106.
22. Terathongkum S, Pickler RH. Relationships among heart rate variability, hypertension, and relaxation techniques. *J Vasc Nurs*. 2004;22:78-82; quiz 83-74.
23. Perasalo J. Traditional use of the sauna for hygiene and health in Finland. *Ann Clin Res* 1988;20:220-223.
24. Valtakari P. The sauna and bathing in different countries. *Ann Clin Res*. 1988;20:230-235.
25. Kukkonen-Harjula K, Kauppinen K. Health effects and risks of sauna bathing. *Int J Circumpolar Health* Jun 2006;65:195-205.
26. Hannuksela ML, Ellahham S. Benefits and risks of sauna bathing. *Am J Med*. 2001;110:118-126.
27. Bruce-Low SS, Cotterrell D, Jones GE. Heart rate variability during high ambient heat exposure. *Aviat Space Environ Med*. 2006;77:915-920.
28. Kuwahata S, Miyata M, Fujita S, et al. Improvement of autonomic nervous activity by Waon therapy in patients with chronic heart failure. *Journal of cardiology*. 2011;57(1): 100-106.
29. Kihara T, Biro S, Ikeda Y, et al. Effects of repeated sauna treatment on ventricular arrhythmias in patients with chronic heart failure. *Circulation Journal*. 2004;68(12): 1146-1151.
30. Kunbootsri N, Janyacharoen T, Arrayawichanon P, et al. The effect of six-weeks of sauna on treatment autonomic nervous system, peak nasal inspiratory flow and lung functions of allergic rhinitis Thai patients. *Asian Pacific Journal of Allergy and Immunology*. 2013;31(2): 142-147.
31. Laukkanen JA, Laaksonen D, Lakka TA, et al. Determinants of cardiorespiratory fitness in men aged 42 to 60 years with and without cardiovascular disease. *Am J Cardiol*. 2009;103:1598-1604.
32. Giles D, Draper N, Neil W. Validity of the Polar V800 heart rate monitor to measure RR intervals at rest. *Eur J Appl Physiol* Mar 2016;116:563-571.

33. Tarvainen MP, Niskanen JP, Lipponen JA, Ranta-Aho PO, Karjalainen PA. Kubios HRV--heart rate variability analysis software. *Comput Methods Programs Biomed* 2014;113:210-220.
34. [Radtke T, Poerschke D, Wilhelm M, Trachsel LD, Tschanz H, Matter F, Jauslin D, Saner H, Schmid JP. Acute effects of Finnish sauna and cold-water immersion on haemodynamic variables and autonomic nervous system activity in patients with heart failure. *Eur J Prev Cardiol.* 2016;23:593-601.](#)
354. Gayda M, Bosquet L, Paillard F, et al. Effects of sauna alone versus postexercise sauna baths on short-term heart rate variability in patients with untreated hypertension. *J Cardiopulm Rehabil Prev.* 2012;32:147-154.
365. Yamamoto S, Iwamoto M, Inoue M, Harada N. Evaluation of the effect of heat exposure on the autonomic nervous system by heart rate variability and urinary catecholamines. *J Occup Health.* 2007;49:199-204.
376. Kukkonen-Harjula K, Oja P, Vuori I, et al. Cardiovascular effects of Atenolol, scopolamine and their combination on healthy men in Finnish sauna baths. *Eur J Appl Physiol Occup Physiol.* 1994;69:10-15.
387. Neves VR, Takahashi AC, do Santos-Hiss MD, et al. Linear and nonlinear analysis of heart rate variability in coronary disease. *Clin Auton Res.* 2012;22:175-183.
- ~~38. Stanley J, Halliday A, D'Auria S, Buehheit M, Leicht AS. Effect of sauna-based heat acclimation on plasma volume and heart rate variability. *Eur J Appl Physiol.* 2015;115:785-794.~~
3939. Leicht AS, Halliday A, Sinclair WH, et al. Heart rate variability responses to acute and repeated postexercise sauna in trained cyclists. *Appl Physiol Nutr Metab.* 2018;43:704-710.
400. Monfredi O, Lyashkov AE, Johnsen AB, et al. Biophysical characterization of the underappreciated and important relationship between heart rate variability and heart rate. *Hypertension.* 2014;64:1334-1343.
411. Monfredi O, Zhang H, Boyett MR. Letter by Monfredi et al Regarding Article, "Physical activity and heart rate variability in older adults: The Cardiovascular Health Study". *Circulation.* 2015;131:e348-e348.
42. [Boyett M, Wang Y, D'Souza A; CrossTalk opposing view: Heart rate variability as a measure of cardiac autonomic responsiveness is fundamentally flawed. *J Physiol.* 2019;597:2599-2601.](#)
43. [Sacha J. Interaction between heart rate and heart rate variability. *Ann Noninvasive Electrocardiol.* 2014;19:207-216.](#)
44. [Billman GE; The effect of heart rate on the heart rate variability response to autonomic interventions. *Front Physiol.* 2013;4:222.](#)
45. [Monfredi O, Lyashkov AE, Johnsen AB, Inada S, Schneider H, Wang R, Nirmalan M, Wisloff U, Maltsev VA, Lakatta EG, Zhang H, Boyett MR. Biophysical characterization of the underappreciated and important relationship between heart rate variability and heart rate. *Hypertension.* 2014;64:1334-1343.](#)
462. Kunutsor SK, Khan H, Laukkanen T, Laukkanen JA. Joint associations of sauna bathing and cardiorespiratory fitness on cardiovascular and all-cause mortality risk: a long-term prospective cohort study. *Ann Med.* 2018;50:139-146.

473. Laukkanen J, Laukkanen T, Khan H, Babar M, Kunutsor SK. Combined effect of sauna bathing and cardiorespiratory fitness on the risk of sudden cardiac deaths in Caucasian men: a long-term prospective cohort study. *Prog Cardiovasc Dis.* 2018;60:635-641.
48. Laukkanen JA, Kurl S, Salonen JT. Cardiorespiratory fitness and physical activity as risk predictors of future atherosclerotic cardiovascular diseases. *Curr Atheroscler Rep.* 2002;4(6):468-476.

Table 1: Characteristics of participants

Variable	N	Value*
Demographic and general parameters		
Age (years)	90	52.0 ± 8.8
Sex (M %)	93	50 (53.8)
Body weight (kg)	88	82.0 ± 15.7
Body mass index (kg/m ²)	88	27.5 ± 4.5
Systolic blood pressure (mmHg)	86	136.9 ± 16.5
Diastolic blood pressure (mmHg)	86	82.2 ± 9.7
Resting HR (bpm)	86	64.8 ± 10.4
Smoking (Yes, %)	90	13 (14.4)
~Hypertension (Yes, %)	91	14 (15.4)
^Hypercholesterolaemia (Yes, %)	91	51 (56.0)
Diabetes (Yes, %)	91	2 (2.2)
Family history of coronary heart disease (Yes, %)	90	28 (31.1)
Cardiorespiratory parameters[§]		
Achieved/Predicted Heart Rate (%)	86	103.6 ± 7.9
Maximum load (watt)	86	228.7 ± 53.5
Cardiorespiratory fitness (METs)	86	9.0 ± 2.1
Blood-based parameters		
Glucose (mmol/l)	91	5.2 ± 0.9
Total cholesterol (Tot Chol; mmol/L)	91	5.4 ± 1.0
Low density lipoprotein (LDL; mmol/L)	91	3.0 ± 0.8
High density lipoprotein (HDL; mmol/L)	91	1.4 ± 0.5
Triglycerides (mmol/L)	91	1.6 (0.9-2.3)
Creatinine (µmol/L)	93	76.3 ± 14.5
Hs-CRP (mg/l)	93	1.2 (0.5-2.5)
Regular typical Sauna use		
Frequency sauna (n/week)	91	
1 session		14 (15.4)
2 sessions		14 (15.4)
3 sessions		43 (47.3)
≥4 sessions		20 (21.9)
Duration sauna (min per session)	90	
≤30		54 (60.0)
30-60		22 (24.4)
≥60		14 (15.6)

*Continuous data are reported as mean ± SD or median (interquartile range) for normally and non-normally distributed variables, respectively; categorical data are shown as number (%).

§ Estimated before (pulse wave velocity) and during cardiopulmonary exercise test

~ Blood pressure medications

^ LDL >5.17 mmol/L

*M = male

Table 2: Characteristics of heart rate variability parameters before, during and after sauna (N=93)

	Time						% mean difference vs. reference (95% CI)	
Variable	1	2	3	4	5	6	5 vs. 1	6 vs. 1
Mean HR (1/min)	76.5 ± 10.3	92.9 ± 15.8	100.4 ± 17.0	119.8 ± 19.0	82.7 ± 15.5	67.9 ± 11.9	+8.1% (5.0, 11.1) ***	-11.3% (-14.0, -8.5) ***
Max HR (1/min)	90.6 ± 12.0	104.2 ± 17.0	112.0 ± 17.9	135.8 ± 19.6	93.2 ± 16.7	76.4 ± 13.0	+2.9% (0.1, 5.6) *	-15.6% (-18.2, -13.0) ***
Min HR (1/min)	66.2 ± 9.8	82.2 ± 14.9	89.8 ± 16.5	104.0 ± 19.0	74.5 ± 14.7	61.3 ± 11.0	+12.5% (8.8, 16.2) ***	-7.5% (-10.8, -4.2) ***
Mean RR (s)	0.8 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.8 ± 0.1	0.9 ± 0.1	-6.3% (-8.4, -4.2) ***	+13.3% (11.0, 15.7) ***
RMSSD (s)	0.02 (0.02-0.03)	0.01 (0.01-0.01)	0.01 (0.00-0.01)	0.00 (0.00-0.01)	0.01 (0.01-0.02)	0.03 (0.02-0.04)	-44.8% (-50.7, -38.9) ***	+10.8% (-1.0, 22.7)
STDRR (s)	0.03 (0.02-0.04)	0.02 (0.01-0.02)	0.01 (0.01-0.02)	0.01 (0.01-0.01)	0.02 (0.01-0.02)	0.03 (0.02-0.04)	-45.6% (-51.0, -40.3) ***	-14.9% (-23.2, -6.5) **
LF power (ms ²)	719 (345-1365)	240 (88-381)	128 (61-294)	56 (18-125)	173 (65-391)	406 (195-763)	-76.2% (-82.0, -70.3) ***	-38.3% (-53.4, -23.2) ***
HF power (ms ²)	156 (86-307)	27 (15-64)	17 (8-42)	7 (3-19)	76 (22-151)	229 (103-444)	-62.8% (-71.2, -54.4) ***	+27.8% (-1.2, 56.8)
Total power (ms ²)	1018 (600-1981)	311 (127-545)	195 (90-461)	78 (28-189)	289 (127-587)	793 (413-1449)	-72.6% (-78.7, -66.6) ***	-25.9% (-42.3, -9.6) **
LF power nu (n.u.)	80.5 (73.4-87.9)	86.4 (78.0-91.8)	88.2 (80.0-92.0)	87.8 (78.6-90.9)	74.1 (64.1-80.9)	64.3 (56.3-78.4)	-11.4% (-16.4, -6.4) ***	-19.6% (-24.1, -15.1) ***
HF power nu (n.u.)	19.5 (12.1-26.5)	13.6 (8.2-22.0)	11.8 (8.0-20.0)	12.2 (9.1-21.4)	25.9 (19.1-35.9)	35.7 (21.6-43.7)	+38.2% (18.0, 58.4) ***	+66.6% (42.2, 91.0) ***

Time 1 = before sauna; 2 = 5-10 minutes in sauna; 3 = 15-20 minutes in sauna; 4 = 25-30 minutes in sauna; 5 = 2-7 minutes after sauna; 6 = in the end of 30 min recovery after sauna

Mean HR = mean heart rate; max HR = maximal heart rate, min HR = minimum heart rate, at the six different measurement points (from 1 to 6); HR is expressed as beats/minute

Mean RR = mean RR interval, RMSSD = root mean square of the successive differences between RR intervals; STDRR= standard deviation of normal RR interval; LF power =low frequency power; HF power = high frequency power; LF power nu = low frequency power normalized; HF power nu = high frequency power normalized; s = seconds; ms = milliseconds

For each time point and variable, data are reported as mean ± SD or median (interquartile range) for normally and non-normally distributed variables, respectively.

Differences are shown as percentage mean differences (95% CI) comparing time 5 vs 1 and time 6 vs 1.

* p-value <0.05

** p-value <0.01

*** p-value <0.001

Highlights

Sauna bathing, an activity that has been a tradition in Finland for thousands of years and mainly used for the purposes of pleasure and relaxation, is becoming increasingly popular in many other populations. Emerging evidence suggests that beyond its use for pleasure, sauna bathing may be linked to several health benefits, which include reduction in the risk of vascular diseases such as high blood pressure, cardiovascular disease, and neurocognitive diseases. It has been postulated that regular sauna bathing may improve cardiovascular function via improved endothelium-dependent dilatation, reduced arterial stiffness, modulation of the autonomic nervous system. This study investigated the effects of sauna bathing on HR and HRV parameters. The study showed that a single sauna exposure leads to significant changes in cardiac autonomic nervous balance as indicated by modulation in the parameters of HRV such as RMSSD, STDRR, LF, HF, and total power.

Recovery from sauna bathing favorably modulates cardiac autonomic nervous system

Running title: Sauna and heart rate variability

Tanjaniina Laukkanen ^{a,b}, Jukka Lipponen ^c, Setor K. Kunutsor ^{d,e}, Francesco Zaccardi ^f, Claudio Gil S. Araújo ^g, Timo H. Mäkikallio ^h, Hassan Khan ⁱ, Peter Willeit ^j, Earric Lee ^k, Sanna Poikonen ^l, Mika Tarvainen ^c, Jari A. Laukkanen ^{a,b,k}

^aInstitute of Public Health and Clinical Nutrition, University of Eastern Finland, Kuopio, Finland

^bCentral Finland Health Care District, Department of Internal Medicine, Jyväskylä, Finland

^cDepartment of Applied Physics, University of Eastern Finland, Kuopio, Finland

^dNational Institute for Health Research Bristol Biomedical Research Centre, University Hospitals Bristol NHS Foundation Trust and University of Bristol, Bristol, UK

^eMusculoskeletal Research Unit, Translational Health Sciences, Bristol Medical School, University of Bristol, Learning & Research Building (Level 1), Southmead Hospital, Bristol, UK

^fDiabetes Research Centre, Leicester General Hospital, University of Leicester, Leicester, UK

^gExercise Medicine Clinic;CLINIMEX, Rio de Janeiro, RJ, Brazil

^hDivision of Cardiology, Department of Internal Medicine, Oulu University Hospital, Oulu, Finland

ⁱDepartment of Medicine, Division of Cardiology, Emory University, Atlanta, GA, US

^jDepartment of Neurology, Medical University Innsbruck, Innsbruck, Austria

^kFaculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland

^lPihlajalinna Clinic, Jyväskylä, Finland

Address for Correspondence:

Jari A. Laukkanen, Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland P.O. Box 35, 40014 Jyväskylä, Finland, tel:+358408053478, E-mail:

jari.a.laukkanen@jyu.fi

Revision 2

Recovery from sauna bathing favorably modulates cardiac autonomic nervous system

Running title: Sauna and heart rate variability

Tanjaniina Laukkanen ^{a,b}, Jukka Lipponen ^c, Setor K. Kunutsor ^{d,e}, Francesco Zaccardi ^f, Claudio Gil S. Araújo ^g, Timo H. Mäkikallio ^h, Hassan Khan ⁱ, Peter Willeit ^j, Earric Lee ^k, Sanna Poikonen ^l, Mika Tarvainen ^c, Jari A. Laukkanen ^{a,b,k}

^aInstitute of Public Health and Clinical Nutrition, University of Eastern Finland, Kuopio, Finland

^bCentral Finland Health Care District, Department of Internal Medicine, Jyväskylä, Finland

^cDepartment of Applied Physics, University of Eastern Finland, Kuopio, Finland

^dNational Institute for Health Research Bristol Biomedical Research Centre, University Hospitals Bristol NHS Foundation Trust and University of Bristol, Bristol, UK

^eMusculoskeletal Research Unit, Translational Health Sciences, Bristol Medical School, University of Bristol, Learning & Research Building (Level 1), Southmead Hospital, Bristol, UK

^fDiabetes Research Centre, Leicester General Hospital, University of Leicester, Leicester, UK

^gExercise Medicine Clinic;CLINIMEX, Rio de Janeiro, RJ, Brazil

^hDivision of Cardiology, Department of Internal Medicine, Oulu University Hospital, Oulu, Finland

ⁱDepartment of Medicine, Division of Cardiology, Emory University, Atlanta, GA, US

^jDepartment of Neurology, Medical University Innsbruck, Innsbruck, Austria

^kFaculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland

^lPihlajalinna Clinic, Jyväskylä, Finland

Address for Correspondence:

Jari A. Laukkanen, Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland P.O. Box 35, 40014 Jyväskylä, Finland, tel:+358408053478, E-mail: jari.a.laukkanen@jyu.fi

Words 4256

Abstract

Objective: Sauna bathing is becoming a common activity in many countries and it has been linked to favorable health outcomes. However, there is limited data on the heart rate (HR) and heart rate variability (HRV) responses to an acute sauna exposure.

Design: We conducted a single-group, time series longitudinal study utilizing a pre-post design to examine acute effects of sauna bathing on the autonomic nervous system as reflected by HRV. A total of 93 participants (mean [SD] age: 52.0 [8.8] years, 53.8% males) with cardiovascular risk factors were exposed to a single sauna session (duration: 30 minutes; temperature: 73°C; humidity: 10-20%) and data on HRV variables were collected before, during and after sauna.

Results: Time and frequency-domain HRV variables were significantly modified ($p < 0.001$) by the single sauna session, with most of HRV variables tending to return near to baseline values after 30 minutes recovery. Resting heart rate was lower at the end of recovery (68/min) compared to pre-sauna (77/min). A sauna session transiently diminished the vagal component, whereas the cooling down period after sauna decreased low frequency power ($p < 0.001$) and increased high frequency power in HRV ($p < 0.001$), favorably modulating the autonomic nervous system balance.

Conclusions: This study demonstrates that a session of sauna bathing induces an increase in heart rate. During the cooling down period from sauna bathing, HRV increased which indicates the dominant role of parasympathetic activity and decreased sympathetic activity of cardiac autonomic nervous system. Future randomized controlled studies are needed to show if HR and HRV changes underpins the long-term cardiovascular effects induced by regular sauna bathing.

Keywords: sauna bathing, heat therapy, heart rate variability, cardiovascular response

1. Introduction

Emerging evidence suggests that sauna bathing, a passive form of heat therapy, has several health benefits.¹ Regular sauna bathing has beneficial effects on the cardiovascular system and which include improved endothelial and microvascular function and reduced arterial stiffness and blood pressure.²⁻⁵ Consistent with these observations, it has been shown that frequent sauna bathing is associated with a reduced risk of dementia,⁶ fatal cardiovascular outcomes and all-cause mortality.⁷ Sauna may favorably modulate the autonomic nervous system, which is a contributing risk factor for cardiovascular disease (CVD).⁸⁻¹⁰ There is a broad body of evidence on the association between cardiac autonomic nervous dysfunction and the risk of fatal arrhythmias.¹¹⁻¹² Regular sauna bathing has been postulated to exert a potential therapeutic effect on blood pressure¹³ which may be partly explained via favorable effects on cardiac autonomic nervous system balance.

Heart rate variability (HRV) is a marker of autonomic nervous system balance, which is a measure of heart rate (HR) fluctuations around the mean HR and has been used to indicate the balance between parasympathetic and sympathetic function of the autonomic nervous system. Higher HRV is indicative of a greater capacity of the cardiovascular system to respond to changes in stressful conditions.¹⁴ A reduced HRV is associated with an increased risk for hypertension, CVD, sudden cardiac death (SCD), and cardiac arrhythmias;^{8,15-17} indeed, autonomic nervous system imbalance with an increased sympathetic or reduced vagal tone has been implicated in the pathophysiology of SCD.^{11,18} HRV analysis provides additional insight into cardiovascular responses to heat exposure. It has been suggested that endurance exercise training and many other physical activities may increase vagal activity and decrease sympathetic activity at rest and recovery.¹⁹⁻²¹ There is evidence to suggest that relaxation techniques may increase HRV.²² Sauna bathing, a common life-style habit used mainly for relaxation and pleasure purposes to release body stress,^{23,24} may have effects on parasympathetic activity of the autonomic nervous system.

Sauna bathing leads to an increase in HR,²⁵ thereby imitating moderate physical activity and its possible effects on autonomic nervous system without active skeletal muscle work. Additionally, it is known that the acute physiological responses to high temperatures during sauna bathing induces fluid loss with an increase in HR.^{25,26} Evidence also suggests that exposure to high ambient temperature is associated with an increase in HRV.²⁷ A number of studies have shown that other passive heat therapies (eg. infrared-ray sauna, Waon therapy, etc) improve cardiac function and autonomic nervous activity in patients with pre-existing conditions such as heart failure and chronic respiratory disease.²⁹⁻³⁰ There is however very limited data on the effects of typical Finnish sauna bathing on autonomic nervous system indices such as HRV in participants with cardiovascular risk factors. Given the overall evidence, we hypothesized that immediately after a single sauna exposure, it is possible to identify favorable cardiac autonomic responses. In this context, we conducted an experimental study to investigate cardiac autonomic nervous system responses, by using HRV measurements, during and immediately after sauna bathing among participant with at least one cardiovascular risk factor.

2. Methods

2.1. Participants

This study was part of the sauna and cardiovascular health study, which has been described in previous reports.^{4,5} Participants (n=93) were recruited from the city of Jyväskylä, Central Finland region, through the local out-of-hospital health care center. The study group consisted of participants without symptomatic CVD who had at least one cardiovascular risk factor, such as a history of smoking, dyslipidemia, hypertension, obesity, diabetes, or family history of coronary heart disease (CHD). Participants with diagnosed CVD were not included in the study. Prior to the participation of the study, all participants were informed about the

research purposes, measurement procedures, and were interviewed and examined by a cardiologist.

The investigation was concordant with the principles outlined in the Declaration of Helsinki and its future amendments. The research protocol and study design were reviewed and approved by the institutional review board of the Central Finland Hospital District ethical committee, Jyväskylä, Finland (Dnro 5U/2016). All participants provided written informed consent.

2.2. Clinical examination

A clinical evaluation with baseline data collection was conducted on a separate day prior to the actual sauna experiment. During the screening visit, medical history, physical examination, and resting electrocardiogram (ECG) were assessed. All baseline and sauna measurements were performed from May to June 2016, as a part of the sauna and cardiovascular health study.⁴ Resting blood pressure was measured as the mean of two measurements, obtained while the participant was supine with a standardized measurement protocol. Body mass index (BMI) was calculated by dividing measured weight in kilograms by the square of height in meters. Assessment of baseline characteristics and diseases were based on a self-reported questionnaire which was checked by a cardiologist during the screening visit. The regular use of medication was assessed by a detailed questionnaire. All questionnaires have been previously validated in a Finnish population-based cohort study.³¹

2.3. Assessment of sauna bathing habits

Previous regular sauna bathing habits were assessed by the questionnaires and the information collected was based on frequency (weekly sauna sessions), duration of sauna exposure, and temperature of the sauna during the exposure. The questionnaires were cross-checked at the time of baseline data collection.

2.4. Sauna exposure

Sauna exposure was based on dry air and relatively high temperature.⁷ Sauna exposure was a typical Finnish sauna bathing session; the total duration was 30 minutes, and it was divided into two 15 minutes sessions with a short, two-minute warm (temperature of 38°C) shower in-between the sessions. The given sauna protocol is applicable for our study population with regard to safety issues and it also corresponds very well with typical sauna use in Finland. The sauna rooms were gender specific. The temperature and humidity were measured continuously by using a 2-channel thermometer in the sauna room (Harvia Co., Finland) and the respective data was collected during the entire experiment. The temperature of sauna was measured at 10 seconds intervals during the sauna sessions. Data obtained via the temperature tracking device showed that the mean temperature was 73 (standard deviation, SD ± 2) °C with a relative humidity of 10-20%.⁴

Experiments were supervised by a physician and participants were given the opportunity to leave the sauna at any time they felt uncomfortable. All participants underwent the recommended sauna protocol successfully. Participants remained in a seated upright position. Immediately after sauna exposure, participants were instructed to rest in a designated relaxing waiting lounge (mean temperature 21°C) for 30 minutes' recovery. To make up for fluid loss due to increased sweating, participants were given 500 mL still water at room temperature for drinking during the entire sauna session, including the recovery period after sauna.^{4,25,26} Body temperature was measured for each participant by the tympanic method (Apteq RA600, Rossmax International Ltd Rossmax Swiss GmbH).

2.5. Assessment of heart rate and heart rate variability

HR and HRV data were collected by a Polar V800 monitor (Polar, Finland), using a chest strap transmitter. Previous findings have shown the validity of the Polar V800 and its ability to produce RR interval recordings consistent with an ECG, and HRV variables derived from

these recordings are also highly comparable.³² Raw HR data was analysed by Kubios HRV system (version 3.0.2),³³ which is an advanced software for HRV analysis. The software computes all the commonly used time-domain and frequency-domain HRV and several nonlinear variables based on beat-to-beat RR interval data.³³

In addition to detailed HR data collection in sauna, the following HRV variables - mean RR interval, root mean square of the successive differences between RR intervals (RMSSD), standard deviation of normal RR intervals (STDRR), low frequency (LF) power, high frequency (HF) power, total power, LF power normalized (nu) and HF power nu - were collected from six different assessment times with the participants placed at stable sitting position before, during and after the sauna exposure (time 1 = before sauna; 2 = 5-10 minutes in sauna; 3 = 15-20 minutes in sauna; 4 = 25-30 minutes in sauna; 5 = 2-7 minutes after sauna; 6 = at the end of 30 min recovery after sauna). These assessment points represent HR and HRV changes from pre-sauna to in-sauna phase until the end of recovery period post sauna allowing us to investigate HR and HRV profile during and in the 30-minute period after a single sauna bathing session. Participants were seated at least 10 minutes in the chair in the quiet lounge room before and after sauna when HR and HRV data was collected. FFT was used for the spectrum estimation. Bandwidths was LF 0.04-0.15 and HF 0.15-0.4. LF and HF powers were expressed both in absolute values (ms^2) and in normalized values (nu). The normalisation of LF and HF was performed by subtracting the very low frequency component (VLF) from the total power. LF and HF were normalized by calculating $\text{LF}/(\text{TP}-\text{VLF}) \times 100$ and $\text{HF}/(\text{TP}-\text{VLF}) \times 100$, respectively, to receive values independent of total power. This procedure reduces the effects of noise due to artifacts and minimizes the effects of the changes in total power on the LF and HF components. RR interval, RMSSD, STDRR were measured in milliseconds (ms) whereas total power, LF and HF were measured in ms^2 .

2.6. Exercise testing

To assess and confirm potential safety issues in our participants with cardiovascular risk factors before sauna exposure, a graded maximal standard clinical (ECG monitoring) exercise test was conducted on a cycle ergometer and the level of cardiorespiratory (aerobic) fitness was assessed.⁴ The exercise test with continuous ECG (CardioSoft software V.1.84, GE Healthcare, Freiburg, Germany) recordings was performed at baseline visit using an electrically braked cycle ergometer (Monark Exercise AB, Sweden). The test was started with 3 minutes' warm-up with no resistance added and continued with 20-watt increments applied each 1 min until volitional exhaustion. Cardiorespiratory fitness was expressed in metabolic equivalents (METs) and maximal exercise workload in watts. All exercise tests were supervised by an experienced physician with the assistance of a trained nurse and were not performed on the same day of sauna session.⁴

2.7. Laboratory analyses

Venous blood samples for the determination of plasma total, high-density lipoprotein (HDL) and low-density lipoprotein (LDL) cholesterol, triglycerides (TG) and plasma glucose concentrations were collected by a qualified laboratory technician from the antecubital vein, into serum and plasma tubes (BD Vacutainer, Plymouth, UK). These analyses were taken to define cardiometabolic risk factor profile on the day participants were screened. All other blood samples for other analyses were taken on the day of the sauna experiment.⁴ Participants were instructed to abstain from strenuous physical activity and sauna use 24h before the blood samples were taken. Whole blood samples were stored for 10 min before being centrifuged at 3500 rpm (Megafuge, Heraeus, Germany) and serum and plasma samples stored at -80°C until analysis using a spectrophotometry analyzer (Konelab 20XTi, Thermo Fisher Scientific, Vantaa, Finland). Venous blood samples for the determination of plasma biomarkers including hs-C-reactive protein and plasma creatinine were analyzed using

chemiluminescent immunoassay by Siemens Immulite 2000 XPi analyzer (Siemens Healthcare Diagnostics Products Ltd., Llanberies, UK).

2.8. Statistical analyses

Data are presented as means (SDs) or median (interquartile range) for continuous variables according to their distribution and as number (proportions) for categorical variables. Normality was checked using the Shapiro-Wilk test as well as through observing the Q-Q-plots. Differences of normally distributed and log-transformed non-normally distributed HRV variables before (time 1), during (times 2, 3, 4) and after (times 5,6) sauna were estimated using repeated measures mixed models with an independent covariance. Before sauna exposure and during the recovery data were analysed for within-group changes with a paired t-test. To investigate possible effects of sauna bathing on autonomic nervous balance during recovery (e.g. changes in parasympathetic activity), we compared HR and HRV before sauna (time 1) to the two assessment points at the recovery phase (time 5 and 6), both of which were defined as after the sauna. Both absolute and relative changes in HR and HRV analyses were performed. The associations between HR responses during sauna with cardiorespiratory fitness, age and BMI were analyzed. The level for significance was set at $p < 0.05$. All statistical analyses were carried out with Stata version 14.1 (Stata Corp, College Station, Texas, U.S.) and results are reported with 95% confidence intervals.

3. Results

The mean (SD) age, BMI, and cardiorespiratory fitness of the participants included in this study were 52.0 (8.8) years, 27.5 (4.5) kg/m², and 9.0 (2.1) METs, respectively. Proportion of current smokers was 14.4% and the resting systolic blood pressure and diastolic blood pressure were 137 (17) and 82 (10) mmHg, respectively. The proportion of participants with hypertension was relatively low (15.4%); hyperlipidemia and a family history of CHD were

common cardiovascular risk factors in the study population (**Table 1**). The majority of participants reported using sauna baths 3 times per week (47.3%); the proportion of those using sauna 1 or 2 times per week was 15.4%. Other characteristics of study's participants are shown in **Table 1**.

Mean temperature of sauna room was 72°C. None of the participants demanded to leave the sauna room before the 30-minute sauna exposure period and no adverse events occurred.

Mean body temperature increased during sauna session and tended to return to pre-sauna values at the end of 30-minute period after sauna - 36.4 (0.5) °C before sauna, 38.4 (0.7) °C immediately after sauna and 36.6 (0.4) °C at recovery ($p < 0.001$) -. Sauna exposure was associated with a statistically significant increase in HR. HR and RMSSD profiles along the six measurements performed in the study are shown in **Figure 1a** and **b**, respectively. Mean HR increased from pre-sauna 77 beats per minute (time 1) to 120 per minute values (time 4). Immediately after sauna, mean HR was 83 beats per minute (time 5), decreasing to 68 beats per minute (time 6) at the end of recovery phase as reported in **Table 2**. Relative changes in HR, compared to baseline, are presented in **Supplementary Figure 1**.

Sauna bathing had significant effects on HRV variables as shown in **Table 2** and **Figure 2**. In addition to HR changes, mean RR interval, RMSSD, STDRR, LF, HF and total power were also changed when comparing pre-sauna values to immediate post sauna and post-30 min after sauna (**Table 2**). Mean RR was significantly higher post 30-min minutes after sauna as compared to pre-sauna levels. When comparing pre-sauna HRV variables to immediately after sauna or after 30 minutes recovery, most of HRV variables changed significantly. The reduction in LF power was -38.3% from pre-sauna to the end of recovery with a parallel increase in HF power of 27.8% (**Table 2**). In addition to total power change, normalized LF (20%) and HF (67 %) power changed significant ($p < 0.001$) from pre-sauna until the end of recovery.

Supplementary Figure 2 shows the relationship of the difference between maximum HR response during sauna vs individual-level characteristics including maximal HR,

cardiorespiratory fitness, age and BMI. The greater the levels of maximum exercise test, the lower the maximum HR level during sauna (up to 50% smaller in participants with maximum exercise HR of around 190-200 bpm). There were no significant associations between the magnitude of HR response during sauna and levels of cardiorespiratory fitness, age or BMI (**Supplementary Figure 2**).

4. Discussion

This single-group time series study investigated the effects of sauna bathing on HR and HRV parameters in adults with risk factors but without diagnosed CVD. The results from this study showed that a single sauna exposure leads to significant changes in cardiac autonomic nervous balance as indicated by changes in the HRV variables, including RMSSD, STDRR, LF, HF, and total power. HRV was favorably modulated after 30 minutes sauna exposure, suggesting a potential beneficial cardiovascular effect and a stress-releasing effect of sauna bathing during the recovery period.

These new results on sauna and HRV are in line with recent population-based study findings which indicate sauna bathing to be associated with reduced risk of CVDs.^{1,7,13} Evidence on the role of Finnish sauna bathing on HRV is very limited, and thus this study provides novel findings on the effects of sauna bathing on autonomic nervous system modulation. Previous evidence on the beneficial effects of sauna on the autonomic nervous system have been based on the long-term effects of other passive heat therapies such as infrared-ray sauna and Waon therapy employed in patients with pre-existing conditions such as chronic heart failure (CHF). In a randomised control trial (RCT) of 4 weeks of Waon therapy versus usual care in patients with CHF, Waon therapy was demonstrated to have beneficial effects on several indices of the autonomic nervous system.²⁸ In another RCT of infrared-ray dry sauna versus no sauna treatment in patients with CHF, HRV was increased after 5 weeks of sauna

treatment.²⁹ Six weeks of Thai sauna treatment in patients with allergic rhinitis led to significant changes in HRV.³⁰

In contrast to these studies, our findings were based on a 30 minute exposure to Finnish sauna in participants with at least one cardiovascular risk factor with no pre-existing history of CVD. It has been shown that LF/HF ratio was increased after the sauna exposure in normal control subjects and patients with coronary artery disease.³⁴ A single sauna session may induce a significant alteration of autonomic cardiovascular control in patients with untreated hypertension who generally experience increased sympathetic and decreased parasympathetic activity.³⁵ These changes in cardiac autonomic nervous system were largely recovered within a period of 15 to 120 minutes after sauna bathing.³⁵ Another study suggested that post-exercise sauna exposure caused mild to moderate changes in resting vagal related HRV.¹⁰ HR response to heat stress is considered to be similar to the physiological cardiovascular response to physical exercise, which may further influence favorably on HRV and cardiac autonomic nervous system. Even mild heat stress has been shown to influence main components of HRV, leading to a reduced HF component and increased LF/HF ratio within minutes of heat exposure.³⁶ In the current study, HRV was lowered during heat exposure, whereas HRV-HF activity, as an indicator of modulation in vagal activity, was substantially increased during the recovery (cooling down) phase from sauna.

This study showed that sauna bathing leads to significant modulation in cardiac autonomic nervous balance including increased parasympathetic activity after sauna bathing as indicated by changes in the balance of RMSSD, STDRR, LF and HF power, and HRV total power variables. High frequency power and HF-power nu increased while LF-power with LF-power nu decreased, which potentially affects favorably on the cardiac autonomic nervous system by increasing vagal tone activity in the 30-minute after sauna period. Increased sweating during sauna bathing is accompanied by reduction in blood pressure and a higher HR, whilst cardiac stroke volume is largely maintained; although a part of blood volume is diverted from the internal organs to peripheral body parts with decreasing venous return which is not

facilitated by active skeletal muscle work. Indeed, comparable with exercise-induced adaptations, heat stress could increase HR up to 150 per minute.²⁶ Exposure to a Finnish sauna bath with an intensive thermal stimulus has been shown to increase HR with a corresponding decrease in HF-HRV component.³⁷ Our study showed that the mean HR increased from 77 beats per minute to 120 per beats minute level, while the highest observed HR of a participant was 150 per minute. Heart rate increased gradually from the beginning of sauna bath until the end, corresponding with an increase in body temperature.

It has been previously proven that hypertension, malignant arrhythmias, coronary artery disease and acute myocardial infarction are associated with a reduction of HRV.^{11,38} Regular physical exercise, perhaps in combination with sauna bathing, is a potential preventive strategy to favorably increase HRV in population, most probably by inducing larger increases in cardiac vagal activity.^{19,20} Regular sauna bathing has been shown to decrease risk of cardiovascular outcomes such as hypertension, fatal CVD events, SCD and neurodegenerative diseases.^{6,7,13} Then, it is highly possible that the benefits of sauna bathing may be partly explained via effects of improved cardiac autonomic nervous system balance.¹ Also, our current study shows an inverse relationship between maximal HR during exercise and HR response to sauna: participants with lower HR levels during maximal exercise test achieved higher HR responses during sauna. It is interesting to note that sauna bathing may increase HR to the level which corresponds with moderate intensity of exercise.

In this study, HRV was measured to detect the modifications in sympatho-vagal activity during (at 73°C degrees) and after sauna (at 21°C degrees) using a common Finnish sauna protocol. The temperature of sauna was stabilized and controlled for every participant and measured at 10 seconds intervals during the sauna sessions. Participants' body temperature increased from the mean level of 36.4°C to 38.4°C immediately after sauna, although body temperature tended to decrease during the 30 minutes recovery period at a normal room temperature back to individual pre-sauna temperature levels. The positive effects on the autonomic nervous system were based on traditional hot and dry Finnish sauna bathing,

which is unlike other types of saunas operating at lower temperatures or heated water immersion.^{2,3} As this is the first study showing acute effects of 30 minutes' sauna exposure imitating a typical sauna session with a short 1-2 minutes 38°C shower combined with 30 minutes recovery period among participants with risk factors, we focused only on immediate effects of sauna bathing on body heat physiology, HR and HRV. However, it is unclear if sauna bathing induced changes in plasma volume might have effect on HRV responses.^{39,40} Among athletes, acute exposure to extreme heat stress via sauna produced alterations in heart rate and cardiac autonomic modulations, with increased RMSSD during a sauna session.⁴¹ Our current study is based on a relatively large number of participants, which provided adequate power to assess changes in HRV variables. In this study, the assessment of HR and HRV were performed using standard measurement protocols using HRV analysis system.³³ The limitations of this study deserve consideration. First, our study was based on a single group intervention pre-post design (without a control group or crossover design), which obviously has limitations compared to RCTs. The lack of a comprehensive control period limits the interpretation of the data on HR and HRV before and after sauna. However, given the pilot experimental nature of the novel study and limited funding available, we considered this design appropriate. Second, we were unable to adjust HRV for HR values, given that it is well established that measures of HRV are nonlinearly dependent on HR.^{42,43} Indeed, it has been suggested that HRV should not be used alone to assess autonomic nervous system activity.^{35,40} However, our study evaluated both HRV and HR, which are two distinct indices of cardiac autonomic function. On the other hand, there are studies indicating that we should not underestimate the possibility that the change in HRV reflect the change in HR. Due to the inverse curvilinear relationship between HR and R-R interval, HR per se can profoundly influence HRV parameters.⁴⁴ Some authors have suggested that HRV is dependent on HR and cannot be used in a simple way to assess autonomic function.⁴⁵ Third, our HRV measurements were not collected with paced breathing and we could not collect any measurements on breathing. We had no respiratory rate data available before, during or after

the sauna bathing, which may partly limit our interpretation with regards to vagal tone changes. Fourth, it would have been appropriate to adjust fluid intake by assessing fluid loss using body weight before and after sauna exposure, however, we aimed to test traditional Finnish sauna habits. Fifth, the intervention was relatively short-term without serial repeated HRV measurements during a longer recovery period. The study design is, however, novel in this context focusing on immediate acute effects of sauna bathing on cardiac autonomic nervous system function. Findings from a previous epidemiological study suggest that to reduce CVD risk, frequent and regular sauna sessions of at least 20 minutes in duration for a single session may be required to exhibit beneficial effects on cardiovascular function.^{1,7} We focused on population with cardiovascular risk factors as they might benefit from lifestyle interventions. The most beneficial duration of sauna has to be defined and as to whether combining a sauna bathing session with physical activity may be more effective with respect to changes in autonomic nervous system balance needs exploration. Indeed, we have previously shown that a combination of good cardiorespiratory fitness levels produced by aerobic exercise and frequent sauna bathing confer more protection on the risk of cardiovascular and all-cause mortality.⁴⁶⁻⁴⁸ Finally, given that sauna bathing is a traditional habit in Finland, all our study participants were regular sauna users (minimum of one sauna session per week) as it was virtually impossible to recruit sauna naïve participants. Findings may therefore be confounded and not be generalizable to other populations that are not familiar with sauna bathing.^{1,32,33}

This study showed the acute effects of a typical Finnish sauna on HR and HRV in a population with cardiovascular risk factors among regular sauna bathers. The results indicate that sauna bathing improves cardiac autonomic nervous system balance, leading to increase in vagal tone and decrease in sympathetic tone, with favorable modulations in HRV variables during the recovery from sauna. We found that a single sauna exposure leads to significant changes in cardiac autonomic nervous balance as indicated by modulation in the parameters of HRV such as RMSSD, STDRR, LF, HF, and total power. Sauna bathing is a

recommendable habit for relaxation, although additional studies are warranted to establish the potential mid- and longer-term effects of sauna bathing on positive autonomic nervous system adaptations. On the basis of this study, HRV was modulated after 30 minutes sauna exposure, suggesting a stress-releasing effect of sauna bathing during the recovery period.

Acknowledgements

This study was supported by the Finnish Funding Agency for Technology and Innovation, Helsinki, Finland.

Conflict of Interest

The authors declare that there are no competing interests.

Figure Legends

Figure 1. Changes in heart rate during and after sauna bathing (a) and changes in root mean square of the successive differences (RMSSD) between RR intervals during and after sauna bathing (b)

Figure 2. Heart rate variability parameters change during and after sauna bathing

References

1. Laukkanen JA, Laukkanen T, Kunutsor SK. Cardiovascular and other health benefits of sauna bathing: A review of evidence. *Mayo Clinic Proceedings*. 2018 93:1111-1121.
2. Brunt VE, Eymann TM, Francisco MA, Howard MJ, Minson CT. Passive heat therapy improves cutaneous microvascular function in sedentary humans via improved nitric oxide-dependent dilation. *J Appl Physiol* (1985). 2016;121:716-723.
3. Brunt VE, Howard MJ, Francisco MA, Ely BR, Minson CT. Passive heat therapy improves endothelial function, arterial stiffness and blood pressure in sedentary humans. *J Physiol Sep* 2016;594:5329-5342.
4. Laukkanen T, Kunutsor SK, Zaccardi F, Lee E, Willeit P, Laukkanen JA. Acute effects of sauna bathing on cardiovascular function. *J Hum Hypertens*. 2018;32:129-138
5. Lee E, Laukkanen T, Kunutsor SK, et al. Sauna exposure leads to improved arterial compliance: Findings from a non-randomised experimental study. *Eur J Prev Cardiol*. 2018;25:130-138
6. Laukkanen T, Kunutsor S, Kauhanen J, Laukkanen JA. Sauna bathing is inversely associated with dementia and Alzheimer's disease in middle-aged Finnish men. *Age Ageing*. 2017;46:245-249.
7. Laukkanen T, Khan H, Zaccardi F, Laukkanen JA. Association between sauna bathing and fatal cardiovascular and all-cause mortality events. *JAMA Internal Medicine*. 2015;175:542-548.
8. Hillebrand S, Gast KB, de Mutsert R, et al. Heart rate variability and first cardiovascular event in populations without known cardiovascular disease: meta-analysis and dose-response meta-regression. *Europace*. 2013;15:742-749.
9. Lietava J, Vohnout B, Valent D, Celko J. Comparison of hemodynamics during hyperthermal immersion and exercise testing in apparently healthy females aged 50-60 years. *Ital Heart J*. 2004;5:511-516.
10. Stanley J, Halliday A, D'Auria S, Buchheit M, Leicht AS. Effect of sauna-based heat acclimation on plasma volume and heart rate variability. *Eur J Appl Physiol*. 2015;115:785-794.
11. Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. *Eur Heart J*. 1996;17:354-381.
12. Sztajzel J. Heart rate variability: a noninvasive electrocardiographic method to measure the autonomic nervous system. *Swiss Med Wkly*. 2004;134:514-522.
13. Zaccardi F, Laukkanen T, Willeit P, Kunutsor SK, Kauhanen J, Laukkanen JA. Sauna bathing and incident hypertension: A prospective cohort study. *Am J Hypertens*. 2017;30:1120-1125.
14. Fiorelli A, Messina G, Chiodini P, et al. Cardiac Autonomic Changes After Thoracic Sympathectomy: A Prospective, Randomized Study. *Ann Thorac Surg*. 2017;103:216-224.
15. Singh JP, Larson MG, Tsuji H, Evans JC, O'Donnell CJ, Levy D. Reduced heart rate variability and new-onset hypertension: insights into pathogenesis of hypertension: the Framingham Heart Study. *Hypertension*. 1998;32:293-297.

16. La Rovere MT, Pinna GD, Maestri R, et al. Short-term heart rate variability strongly predicts sudden cardiac death in chronic heart failure patients. *Circulation*. 2003;107:565-570.
17. Meyerfeldt U, Wessel N, Schutt H, et al. Heart rate variability before the onset of ventricular tachycardia: differences between slow and fast arrhythmias. *Int J Cardiol* Aug 2002;84:141-151.
18. Maheshwari A, Norby FL, Soliman EZ, et al. Low heart rate variability in a 2-minute electrocardiogram recording Is associated with an increased risk of sudden cardiac death in the general population: The Atherosclerosis Risk in Communities Study. *PLoS One*. 2016;11:e0161648.
19. Murad K, Brubaker PH, Fitzgerald DM, et al. Exercise training improves heart rate variability in older patients with heart failure: a randomized, controlled, single-blinded trial. *Congest Heart Fail* 2012 Jul-Aug 2012;18:192-197.
20. Routledge FS, Campbell TS, McFetridge-Durdle JA, Bacon SL. Improvements in heart rate variability with exercise therapy. *Can J Cardiol*. 2010;26:303-312.
21. Messina G, Vicidomini C, Viggiano A, et al. Enhanced parasympathetic activity of sportive women is paradoxically associated to enhanced resting energy expenditure. *Autonomic Neuroscience: Basic and Clinical*. 2012;169:102-106.
22. Terathongkum S, Pickler RH. Relationships among heart rate variability, hypertension, and relaxation techniques. *J Vasc Nurs*. 2004;22:78-82; quiz 83-74.
23. Perasalo J. Traditional use of the sauna for hygiene and health in Finland. *Ann Clin Res* 1988;20:220-223.
24. Valtakari P. The sauna and bathing in different countries. *Ann Clin Res*. 1988;20:230-235.
25. Kukkonen-Harjula K, Kauppinen K. Health effects and risks of sauna bathing. *Int J Circumpolar Health* Jun 2006;65:195-205.
26. Hannuksela ML, Ellahham S. Benefits and risks of sauna bathing. *Am J Med*. 2001;110:118-126.
27. Bruce-Low SS, Cotterrell D, Jones GE. Heart rate variability during high ambient heat exposure. *Aviat Space Environ Med*. 2006;77:915-920.
28. Kuwahata S, Miyata M, Fujita S, et al. Improvement of autonomic nervous activity by Waon therapy in patients with chronic heart failure. *Journal of cardiology*. 2011;57(1): 100-106.
29. Kihara T, Biro S, Ikeda Y, et al. Effects of repeated sauna treatment on ventricular arrhythmias in patients with chronic heart failure. *Circulation Journal*. 2004;68(12): 1146-1151.
30. Kunbootsri N, Janyacharoen T, Arrayawichanon P, et al. The effect of six-weeks of sauna on treatment autonomic nervous system, peak nasal inspiratory flow and lung functions of allergic rhinitis Thai patients. *Asian Pacific Journal of Allergy and Immunology*. 2013;31(2): 142-147.
31. Laukkanen JA, Laaksonen D, Lakka TA, et al. Determinants of cardiorespiratory fitness in men aged 42 to 60 years with and without cardiovascular disease. *Am J Cardiol*. 2009;103:1598-1604.
32. Giles D, Draper N, Neil W. Validity of the Polar V800 heart rate monitor to measure RR intervals at rest. *Eur J Appl Physiol* Mar 2016;116:563-571.

33. Tarvainen MP, Niskanen JP, Lipponen JA, Ranta-Aho PO, Karjalainen PA. Kubios HRV--heart rate variability analysis software. *Comput Methods Programs Biomed* 2014;113:210-220.
34. Radtke T, Poerschke D, Wilhelm M, Trachsel LD, Tschanz H, Matter F, Jauslin D, Saner H, Schmid JP. Acute effects of Finnish sauna and cold-water immersion on haemodynamic variables and autonomic nervous system activity in patients with heart failure. *Eur J Prev Cardiol.* 2016;23:593-601.
35. Gayda M, Bosquet L, Paillard F, et al. Effects of sauna alone versus postexercise sauna baths on short-term heart rate variability in patients with untreated hypertension. *J Cardiopulm Rehabil Prev.* 2012;32:147-154.
36. Yamamoto S, Iwamoto M, Inoue M, Harada N. Evaluation of the effect of heat exposure on the autonomic nervous system by heart rate variability and urinary catecholamines. *J Occup Health.* 2007;49:199-204.
37. Kukkonen-Harjula K, Oja P, Vuori I, et al. Cardiovascular effects of Atenolol, scopolamine and their combination on healthy men in Finnish sauna baths. *Eur J Appl Physiol Occup Physiol.* 1994;69:10-15.
38. Neves VR, Takahashi AC, do Santos-Hiss MD, et al. Linear and nonlinear analysis of heart rate variability in coronary disease. *Clin Auton Res.* 2012;22:175-183.
39. Leicht AS, Halliday A, Sinclair WH, et al. Heart rate variability responses to acute and repeated postexercise sauna in trained cyclists. *Appl Physiol Nutr Metab.* 2018;43:704-710.
40. Monfredi O, Lyashkov AE, Johnsen AB, et al. Biophysical characterization of the underappreciated and important relationship between heart rate variability and heart rate. *Hypertension.* 2014;64:1334-1343.
41. Monfredi O, Zhang H, Boyett MR. Letter by Monfredi et al Regarding Article, "Physical activity and heart rate variability in older adults: The Cardiovascular Health Study". *Circulation.* 2015;131:e348-e348.
42. Boyett M, Wang Y, D'Souza A; CrossTalk opposing view: Heart rate variability as a measure of cardiac autonomic responsiveness is fundamentally flawed. *J Physiol.* 2019;597:2599-2601.
43. Sacha J. Interaction between heart rate and heart rate variability. *Ann Noninvasive Electrocardiol.* 2014;19:207-216.
44. Billman GE; The effect of heart rate on the heart rate variability response to autonomic interventions. *Front Physiol.* 2013;4:222.
45. Monfredi O, Lyashkov AE, Johnsen AB, Inada S, Schneider H, Wang R, Nirmalan M, Wisloff U, Maltsev VA, Lakatta EG, Zhang H, Boyett MR. Biophysical characterization of the underappreciated and important relationship between heart rate variability and heart rate. *Hypertension.* 2014;64:1334-1343.
46. Kunutsor SK, Khan H, Laukkanen T, Laukkanen JA. Joint associations of sauna bathing and cardiorespiratory fitness on cardiovascular and all-cause mortality risk: a long-term prospective cohort study. *Ann Med.* 2018;50:139-146.
47. Laukkanen J, Laukkanen T, Khan H, Babar M, Kunutsor SK. Combined effect of sauna bathing and cardiorespiratory fitness on the risk of sudden cardiac deaths in Caucasian men: a long-term prospective cohort study. *Prog Cardiovasc Dis.* 2018;60:635-641.

48. Laukkanen JA, Kurl S, Salonen JT. Cardiorespiratory fitness and physical activity as risk predictors of future atherosclerotic cardiovascular diseases. *Curr Atheroscler Rep.* 2002;4:468-476.

Table 1: Characteristics of participants

Variable	N	Value*
Demographic and general parameters		
Age (years)	90	52.0 ± 8.8
Sex (M %)	93	50 (53.8)
Body weight (kg)	88	82.0 ± 15.7
Body mass index (kg/m ²)	88	27.5 ± 4.5
Systolic blood pressure (mmHg)	86	136.9 ± 16.5
Diastolic blood pressure (mmHg)	86	82.2 ± 9.7
Resting HR (bpm)	86	64.8 ± 10.4
Smoking (Yes, %)	90	13 (14.4)
~Hypertension (Yes, %)	91	14 (15.4)
^Hypercholesterolaemia (Yes, %)	91	51 (56.0)
Diabetes (Yes, %)	91	2 (2.2)
Family history of coronary heart disease (Yes, %)	90	28 (31.1)
Cardiorespiratory parameters[§]		
Achieved/Predicted Heart Rate (%)	86	103.6 ± 7.9
Maximum load (watt)	86	228.7 ± 53.5
Cardiorespiratory fitness (METs)	86	9.0 ± 2.1
Blood-based parameters		
Glucose (mmol/l)	91	5.2 ± 0.9
Total cholesterol (Tot Chol; mmol/L)	91	5.4 ± 1.0
Low density lipoprotein (LDL; mmol/L)	91	3.0 ± 0.8
High density lipoprotein (HDL; mmol/L)	91	1.4 ± 0.5
Triglycerides (mmol/L)	91	1.6 (0.9-2.3)
Creatinine (μmol/L)	93	76.3 ± 14.5
Hs-CRP (mg/l)	93	1.2 (0.5-2.5)
Regular typical Sauna use		
Frequency sauna (n/week)	91	
1 session		14 (15.4)
2 sessions		14 (15.4)
3 sessions		43 (47.3)
≥4 sessions		20 (21.9)
Duration sauna (min per session)	90	
≤30		54 (60.0)
30-60		22 (24.4)
≥60		14 (15.6)

*Continuous data are reported as mean ± SD or median (interquartile range) for normally and non-normally distributed variables, respectively; categorical data are shown as number (%).

§ Estimated before (pulse wave velocity) and during cardiopulmonary exercise test

~ Blood pressure medications

^ LDL >5.17 mmol/L

*M = male

Table 2: Characteristics of heart rate variability parameters before, during and after sauna (N=93)

	Time						% mean difference vs. reference (95% CI)	
Variable	1	2	3	4	5	6	5 vs. 1	6 vs. 1
Mean HR (1/min)	76.5 ± 10.3	92.9 ± 15.8	100.4 ± 17.0	119.8 ± 19.0	82.7 ± 15.5	67.9 ± 11.9	+8.1% (5.0, 11.1) ***	-11.3% (-14.0, -8.5) ***
Max HR (1/min)	90.6 ± 12.0	104.2 ± 17.0	112.0 ± 17.9	135.8 ± 19.6	93.2 ± 16.7	76.4 ± 13.0	+2.9% (0.1, 5.6) *	-15.6% (-18.2, -13.0) ***
Min HR (1/min)	66.2 ± 9.8	82.2 ± 14.9	89.8 ± 16.5	104.0 ± 19.0	74.5 ± 14.7	61.3 ± 11.0	+12.5% (8.8, 16.2) ***	-7.5% (-10.8, -4.2) ***
Mean RR (s)	0.8 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.8 ± 0.1	0.9 ± 0.1	-6.3% (-8.4, -4.2) ***	+13.3% (11.0, 15.7) ***
RMSSD (s)	0.02 (0.02-0.03)	0.01 (0.01-0.01)	0.01 (0.00-0.01)	0.00 (0.00-0.01)	0.01 (0.01-0.02)	0.03 (0.02-0.04)	-44.8% (-50.7, -38.9) ***	+10.8% (-1.0, 22.7)
STDRR (s)	0.03 (0.02-0.04)	0.02 (0.01-0.02)	0.01 (0.01-0.02)	0.01 (0.01-0.01)	0.02 (0.01-0.02)	0.03 (0.02-0.04)	-45.6% (-51.0, -40.3) ***	-14.9% (-23.2, -6.5) **
LF power (ms ²)	719 (345-1365)	240 (88-381)	128 (61-294)	56 (18-125)	173 (65-391)	406 (195-763)	-76.2% (-82.0, -70.3) ***	-38.3% (-53.4, -23.2) ***
HF power (ms ²)	156 (86-307)	27 (15-64)	17 (8-42)	7 (3-19)	76 (22-151)	229 (103-444)	-62.8% (-71.2, -54.4) ***	+27.8% (-1.2, 56.8)
Total power (ms ²)	1018 (600-1981)	311 (127-545)	195 (90-461)	78 (28-189)	289 (127-587)	793 (413-1449)	-72.6% (-78.7, -66.6) ***	-25.9% (-42.3, -9.6) **
LF power nu (n.u.)	80.5 (73.4-87.9)	86.4 (78.0-91.8)	88.2 (80.0-92.0)	87.8 (78.6-90.9)	74.1 (64.1-80.9)	64.3 (56.3-78.4)	-11.4% (-16.4, -6.4) ***	-19.6% (-24.1, -15.1) ***
HF power nu (n.u.)	19.5 (12.1-26.5)	13.6 (8.2-22.0)	11.8 (8.0-20.0)	12.2 (9.1-21.4)	25.9 (19.1-35.9)	35.7 (21.6-43.7)	+38.2% (18.0, 58.4) ***	+66.6% (42.2, 91.0) ***

Time 1 = before sauna; 2 = 5-10 minutes in sauna; 3 = 15-20 minutes in sauna; 4 = 25-30 minutes in sauna; 5 = 2-7 minutes after sauna; 6 = in the end of 30 min recovery after sauna

Mean HR = mean heart rate; max HR = maximal heart rate, min HR = minimum heart rate, at the six different measurement points (from 1 to 6); HR is expressed as beats/minute

Mean RR = mean RR interval, RMSSD = root mean square of the successive differences between RR intervals; STDRR= standard deviation of normal RR interval; LF power =low frequency power; HF power = high frequency power; LF power nu = low frequency power normalized; HF power nu = high frequency power normalized; s = seconds; ms = milliseconds

For each time point and variable, data are reported as mean ± SD or median (interquartile range) for normally and non-normally distributed variables, respectively.

Differences are shown as percentage mean differences (95% CI) comparing time 5 vs 1 and time 6 vs 1.

* p-value <0.05

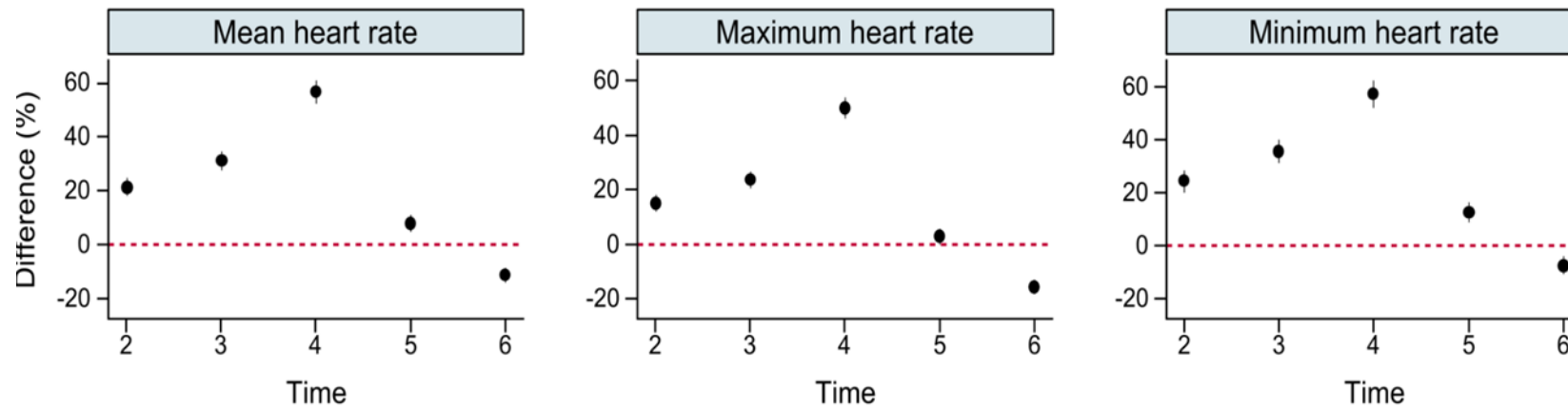
** p-value <0.01

*** p-value <0.001

Recovery from sauna bathing favorably modulates cardiac autonomic nervous system

Relative changes in heart rate (%) during and after sauna, compared to baseline heart rate

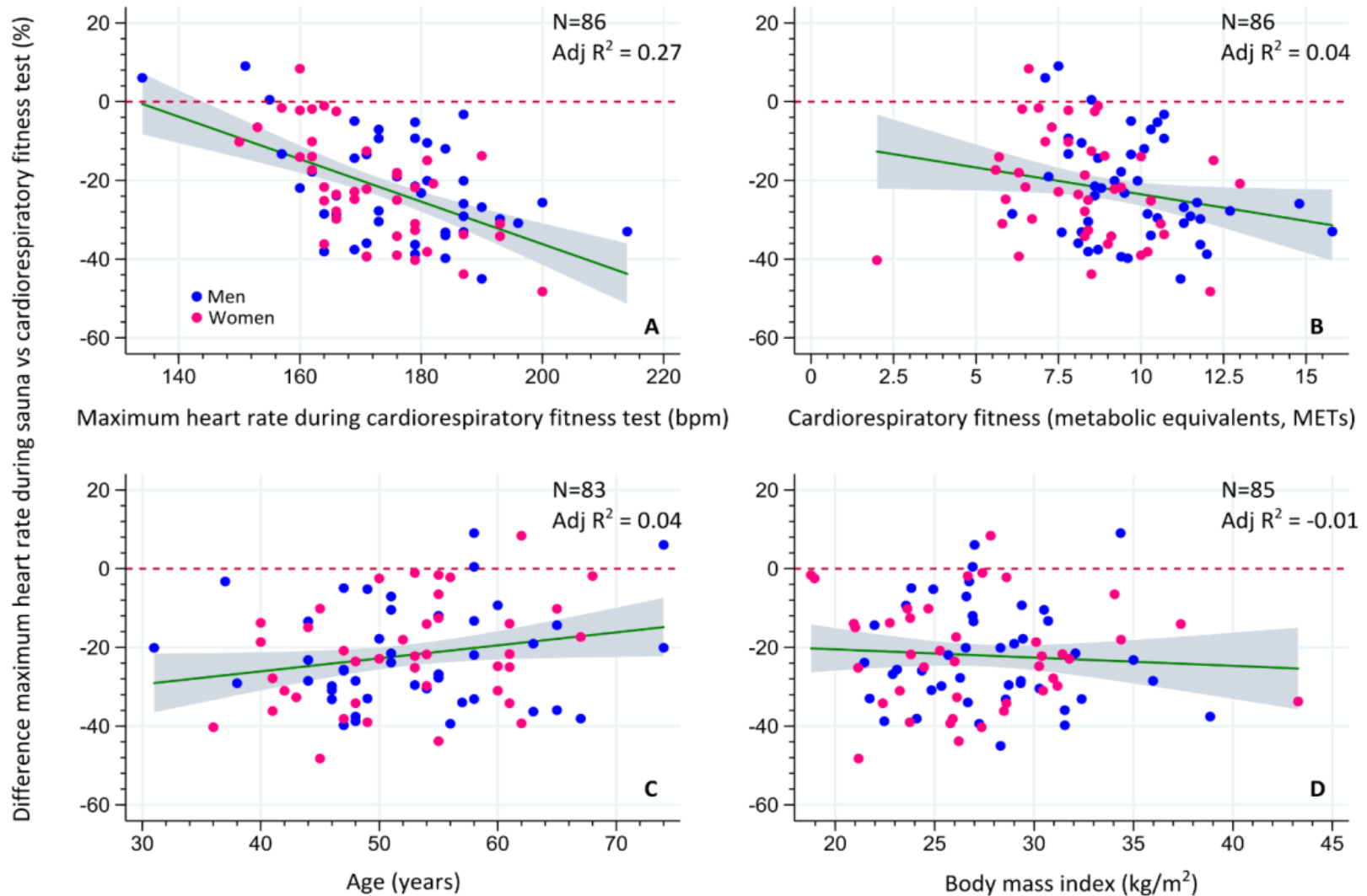
Supplementary Figure 1. Relative changes in heart rate during and after sauna



Percentage differences are reported for each time point vs baseline (time 1, pre-sauna). Estimates whose confidence intervals (spikes) do not cross the zero lines (red dotted lines) are statistically significant different ($p < 0.05$) compared to time 1.

Time 1 = before sauna; 2 = 5-10 minutes in sauna; 3 = 15-20 minutes in sauna; 4 = 25-30 minutes in sauna; 5 = 2-7 minutes after sauna; 6 = in the end of 30 min recovery after sauna

Supplementary Figure 2. Heart rate response during sauna vs individual-level characteristics including maximal heart rate, cardiorespiratory fitness, age and body mass index



The graph shows the relationship of the difference between maximum heart rate (HR) during sauna and cardiorespiratory fitness (CRF) test (y-axis) with four individual-level characteristics (x-axes): maximum HR during CRF test (A), CRF levels (B), age (C), and body mass index (D). Negative values for the y-axis indicate lower maximum HR during sauna compared to CRF test. Maximum HR for sauna was at time point 4. The green line and the shadow area indicate the predicted relationship and 95% confidence interval, respectively.